

# Sea ice-Ocean Variability in the Labrador Sea

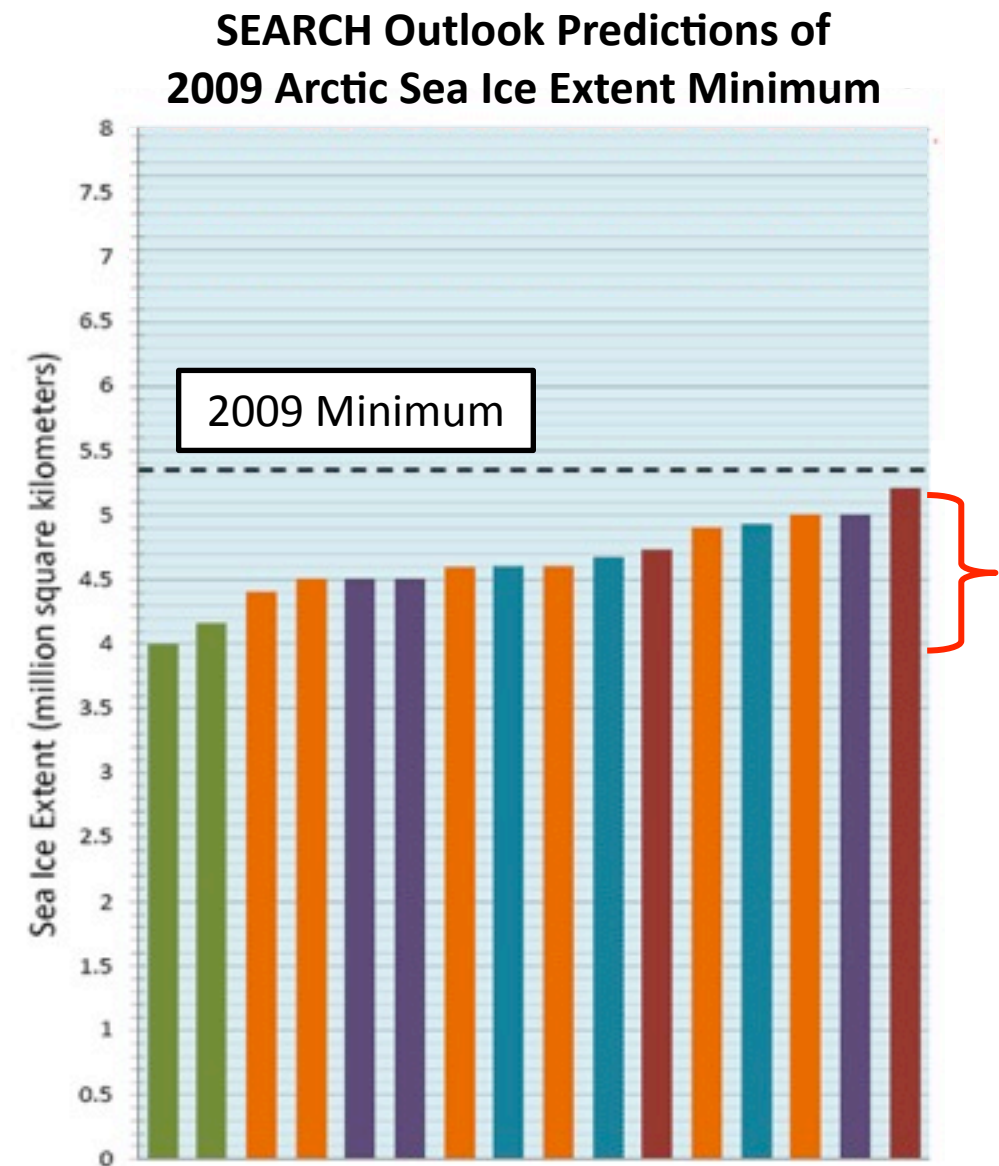
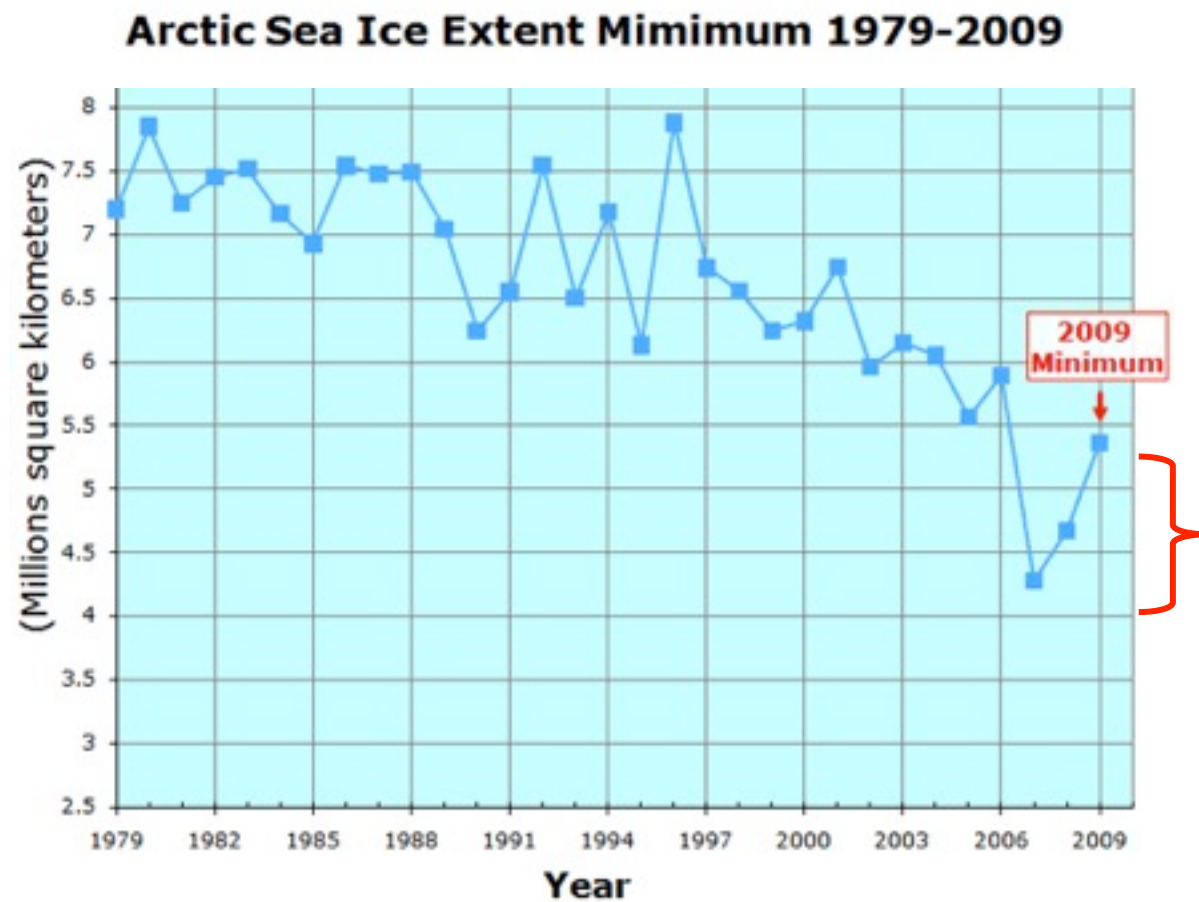
Ian Fenty, Patrick Heimbach, Carl Wunsch



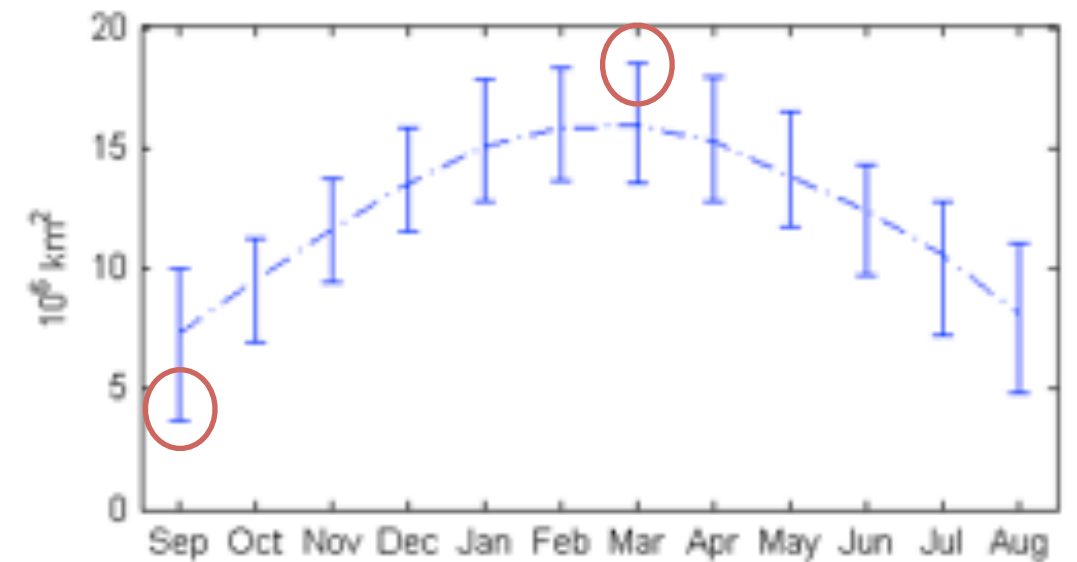
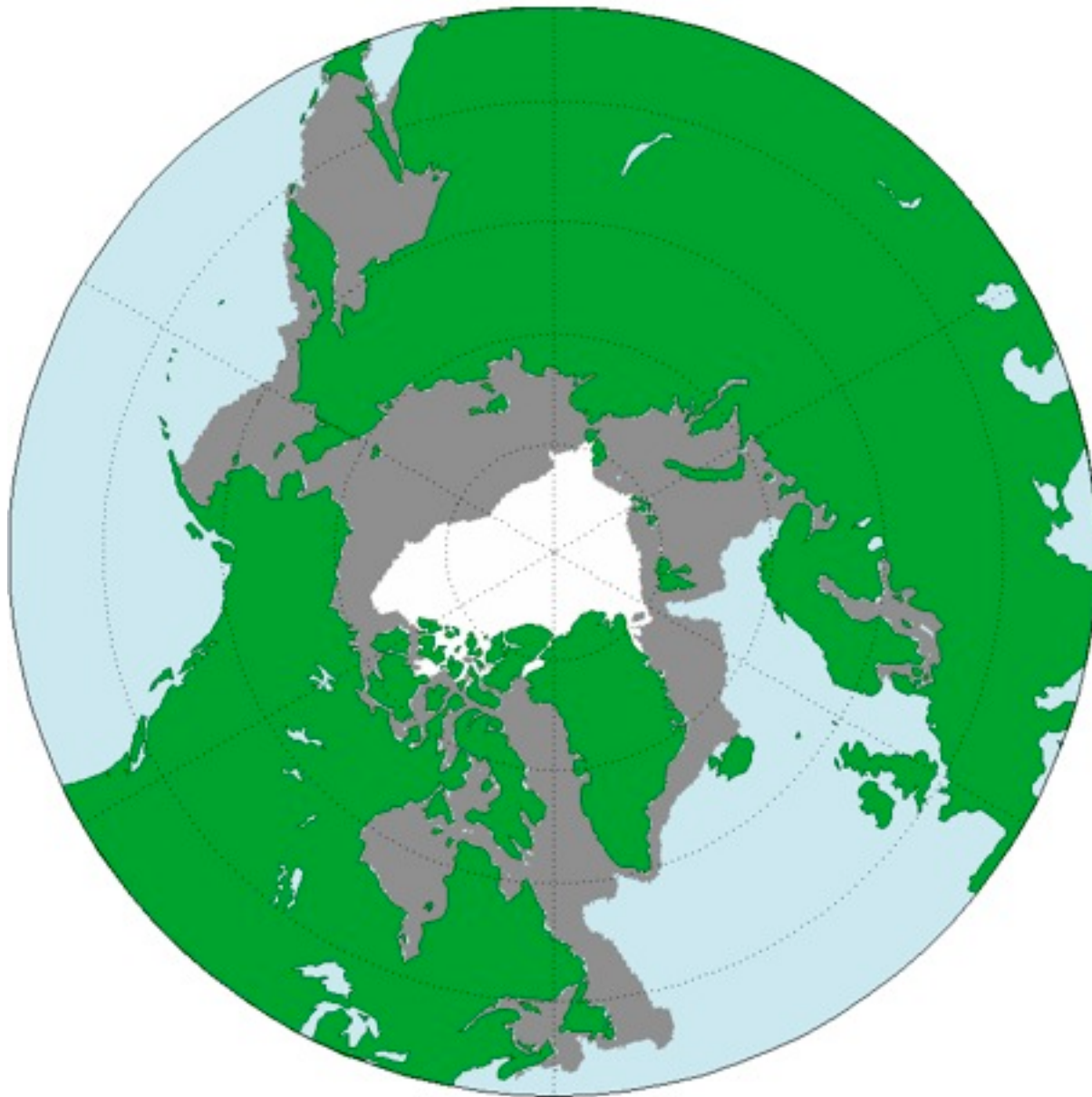
Sea ice on the Labrador Coast March 30, 1999

Image c

Actual 2009 perennial ice minimum was not even within the *range* of 3-month predictions.

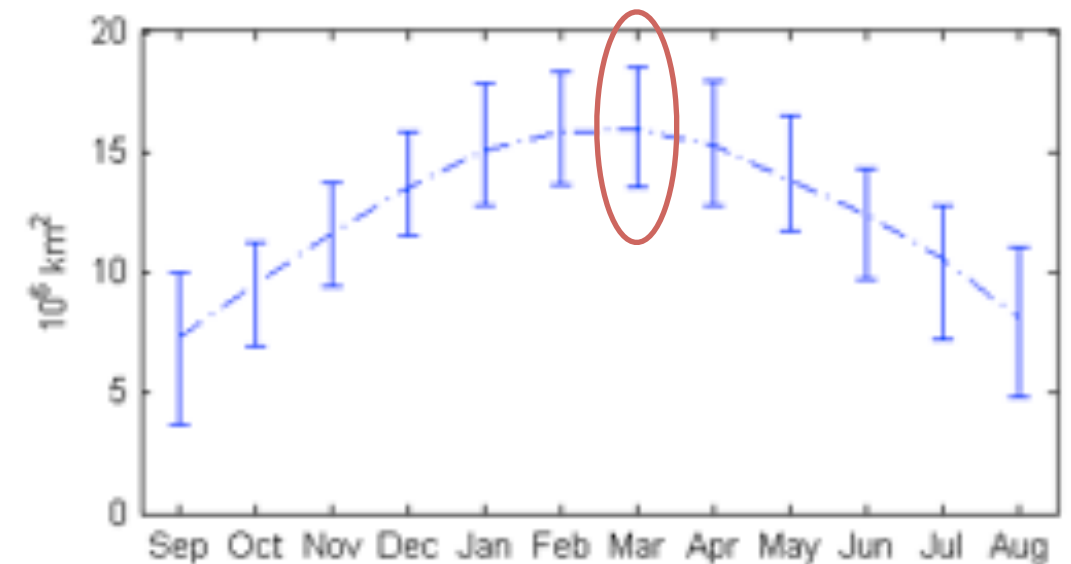
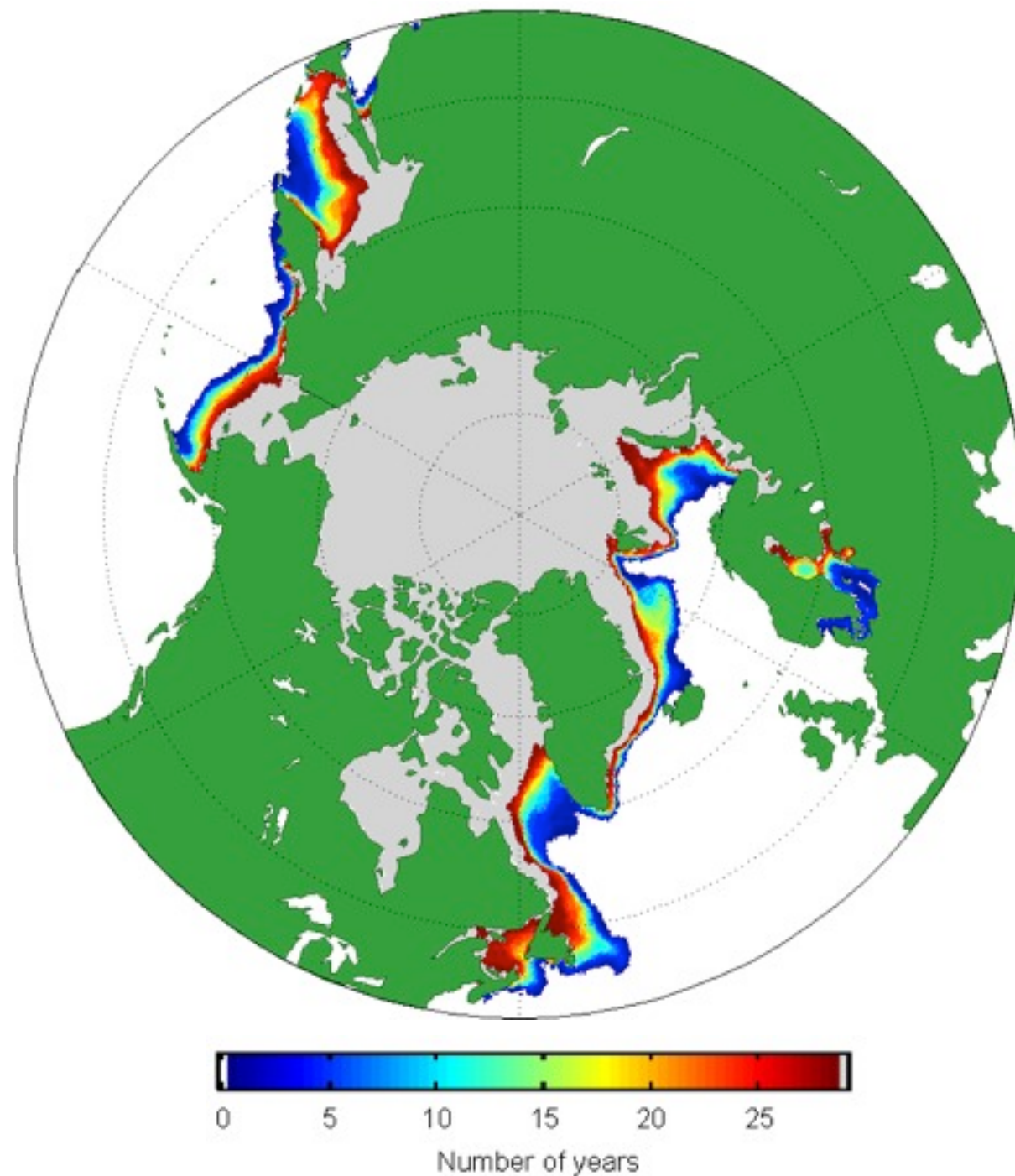


Area of wintertime seasonal ice exceeds perennial ice by factor of 1.5 to 4.



Sea ice extent statistics in the Northern Hemisphere

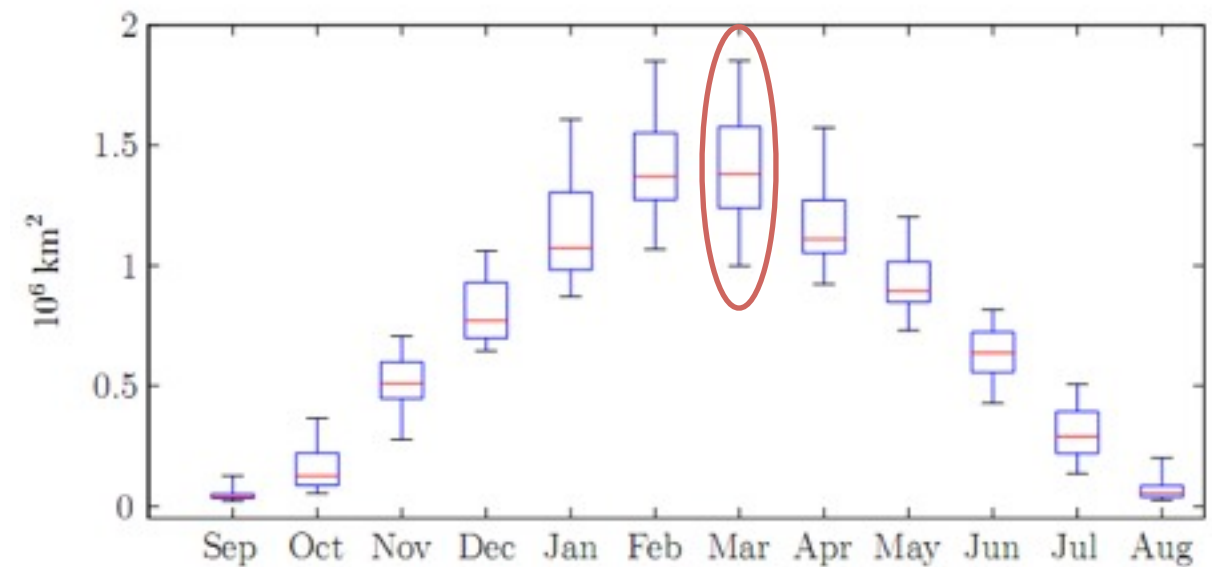
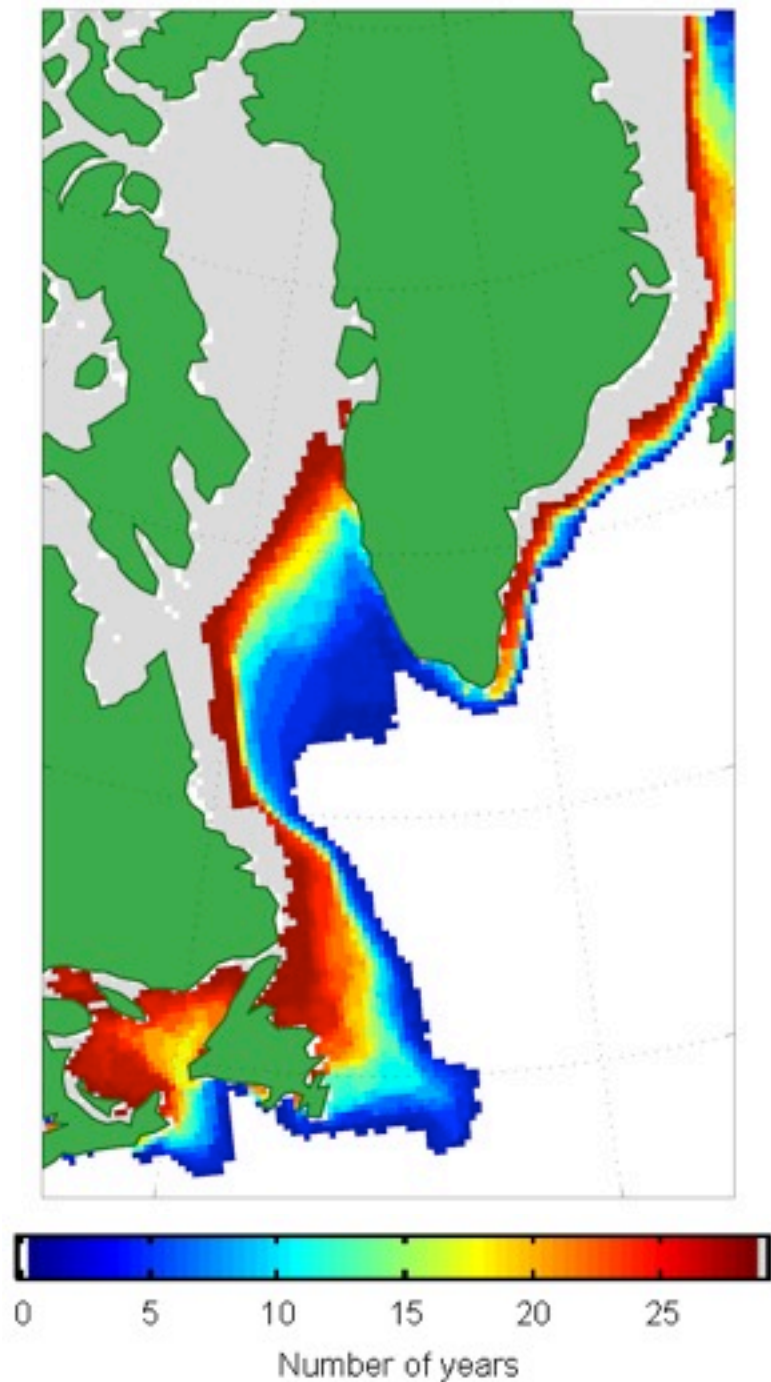
Wintertime seasonal ice extents are highly variable in the marginal polar and subpolar seas.



Sea ice extent statistics in the Northern Hemisphere

1979-2008

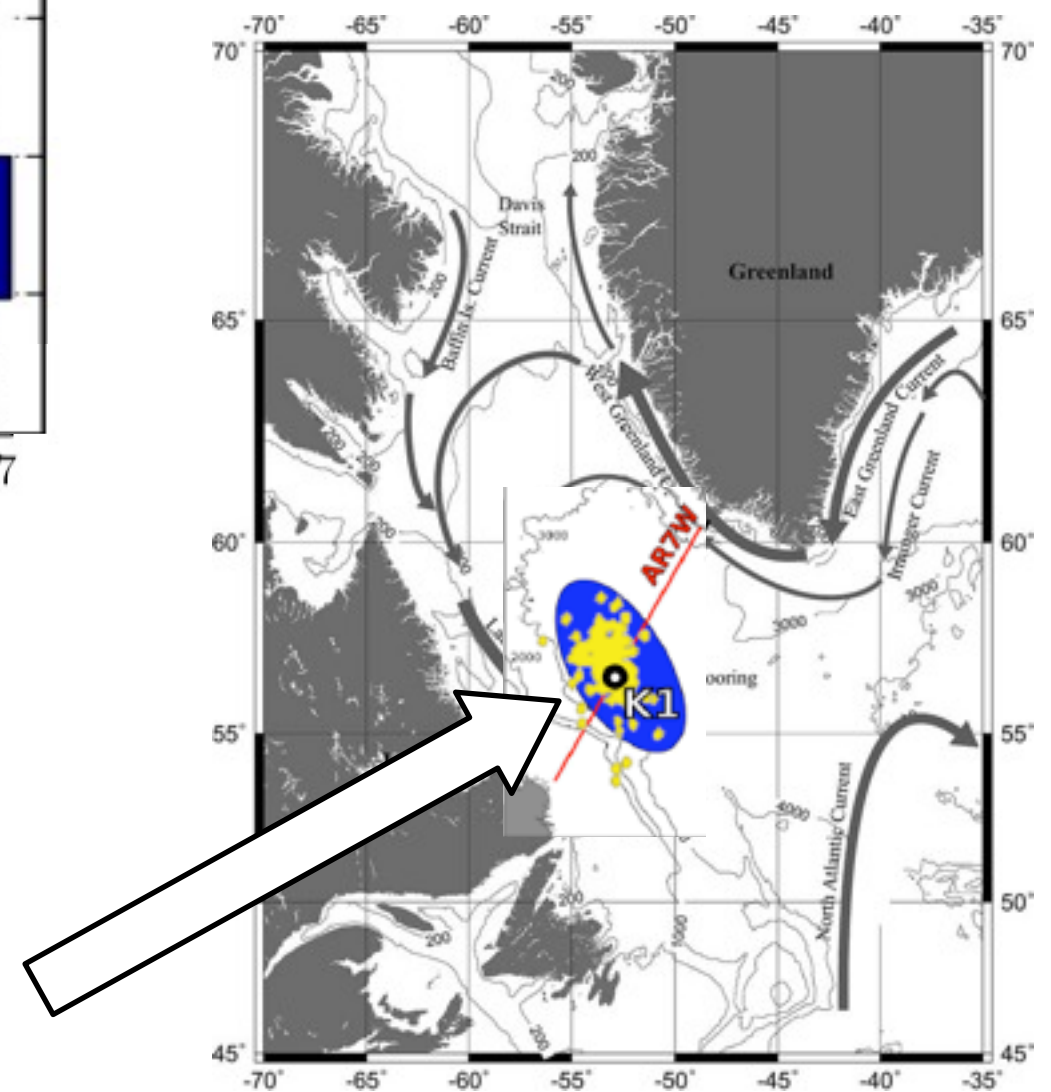
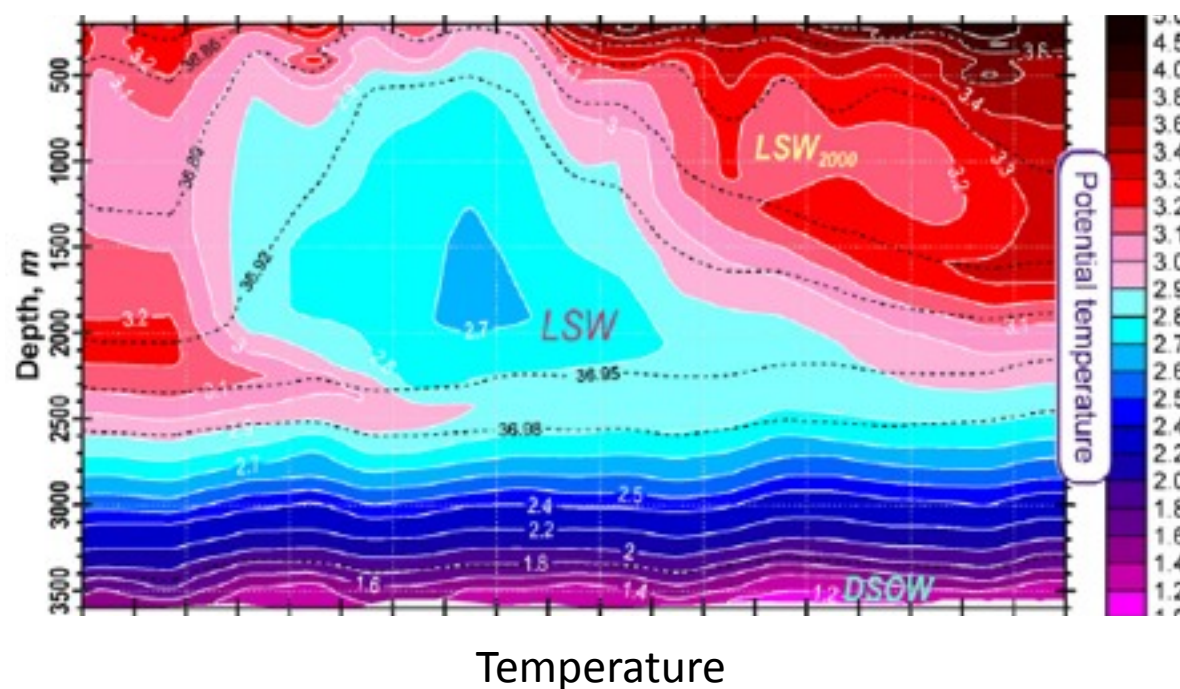
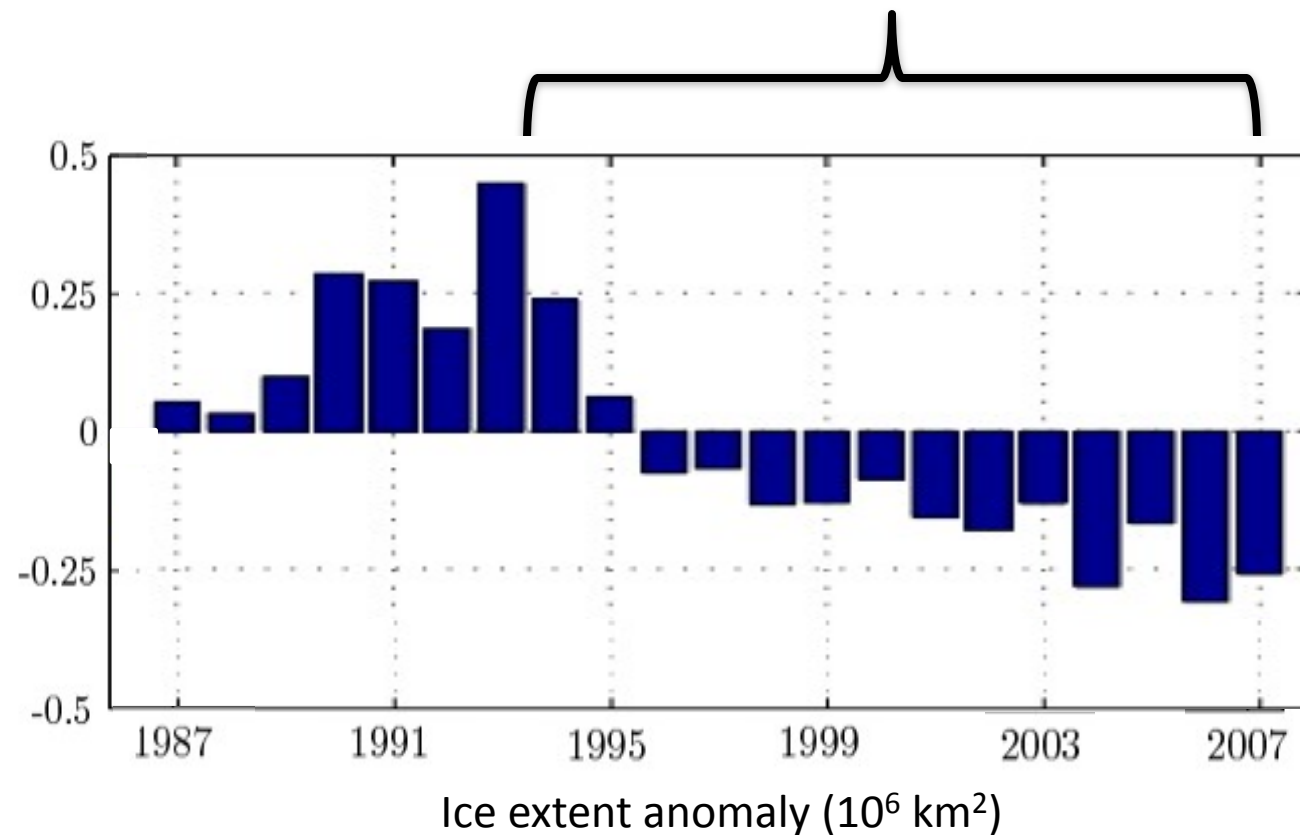
Wintertime seasonal ice extents are highly variable in the Labrador Sea.



Sea ice extent statistics in the Labrador Sea and Baffin Bay

1979-2008

Negative ice extent trend and coincides with Labrador Sea warming and salinification.

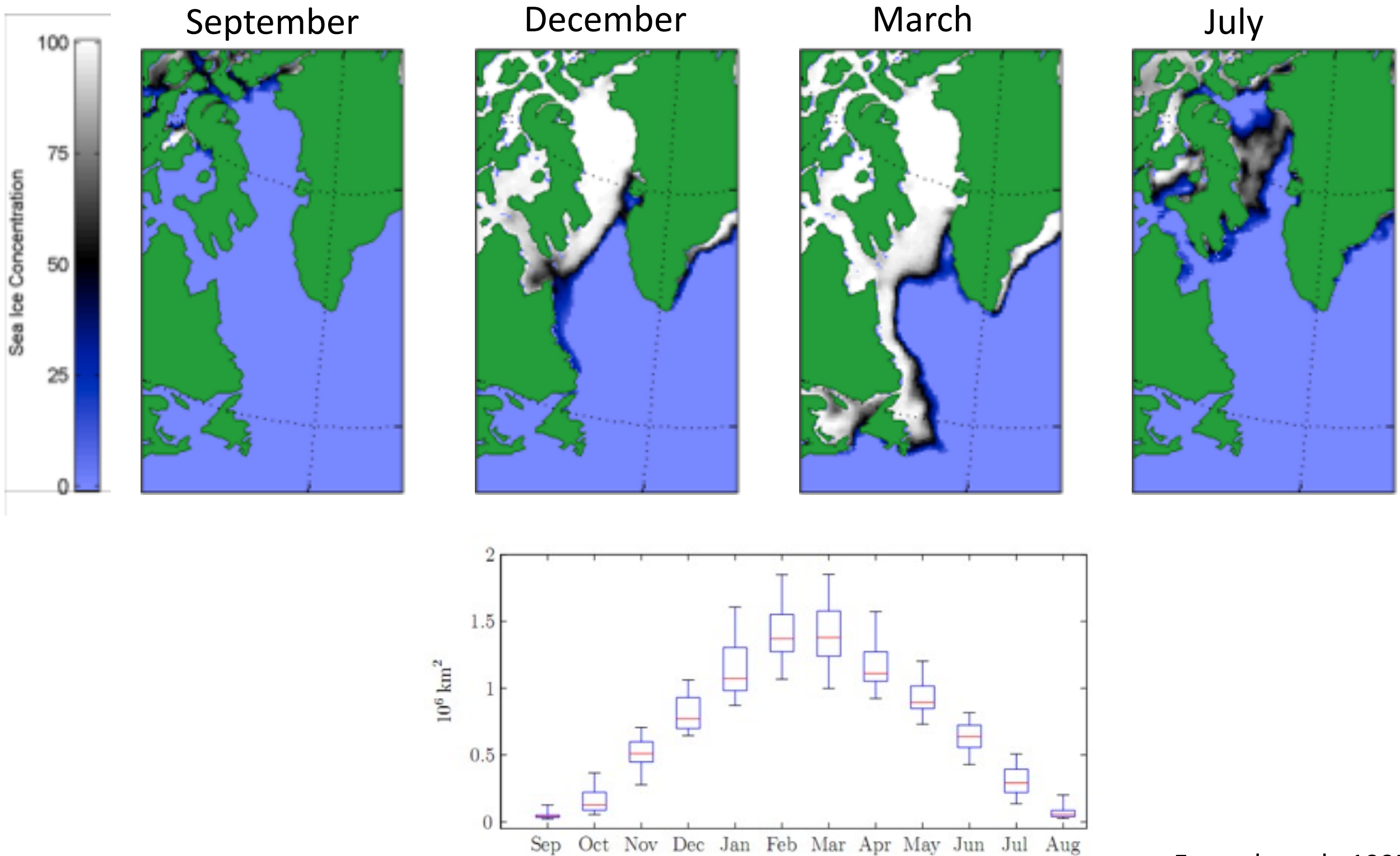


- Part I : Theories of seasonal sea ice variability in the Labrador Sea
- Part II : The synthesis of model and data
- Part III : Hydrographic and sea ice variability in the Labrador Sea

# Part I: Theories of seasonal sea ice variability in the Labrador Sea

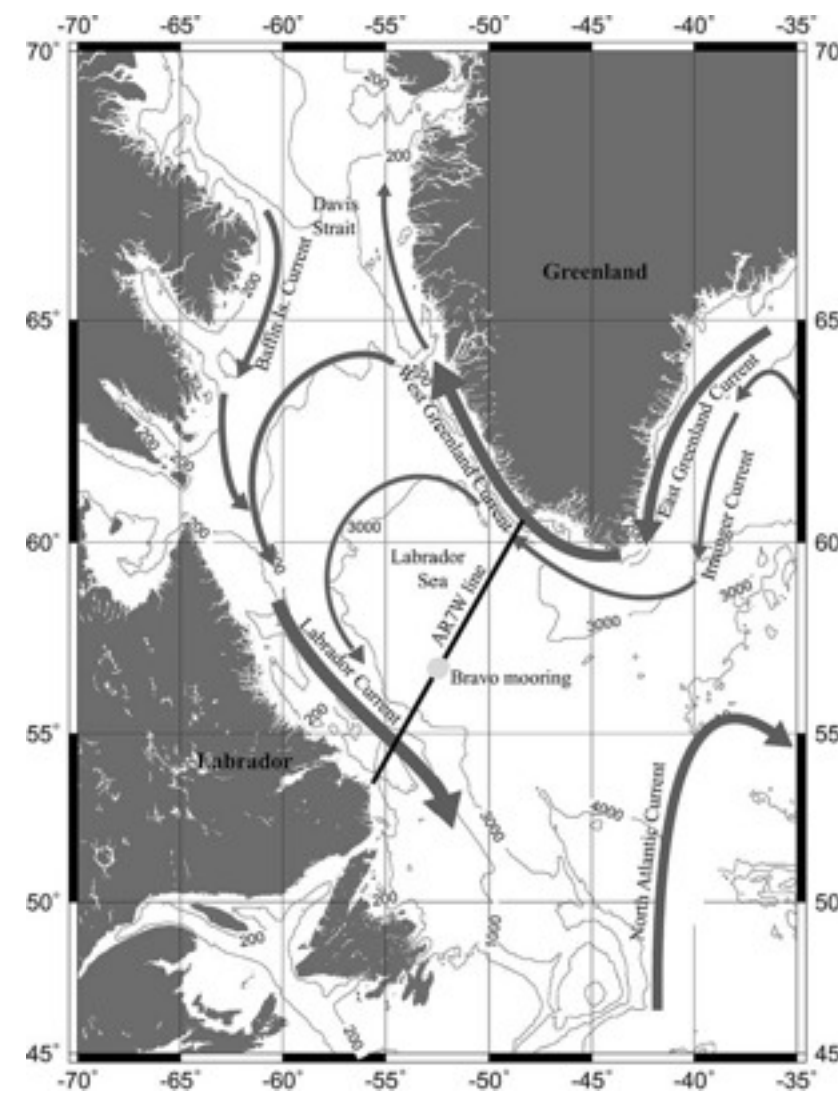
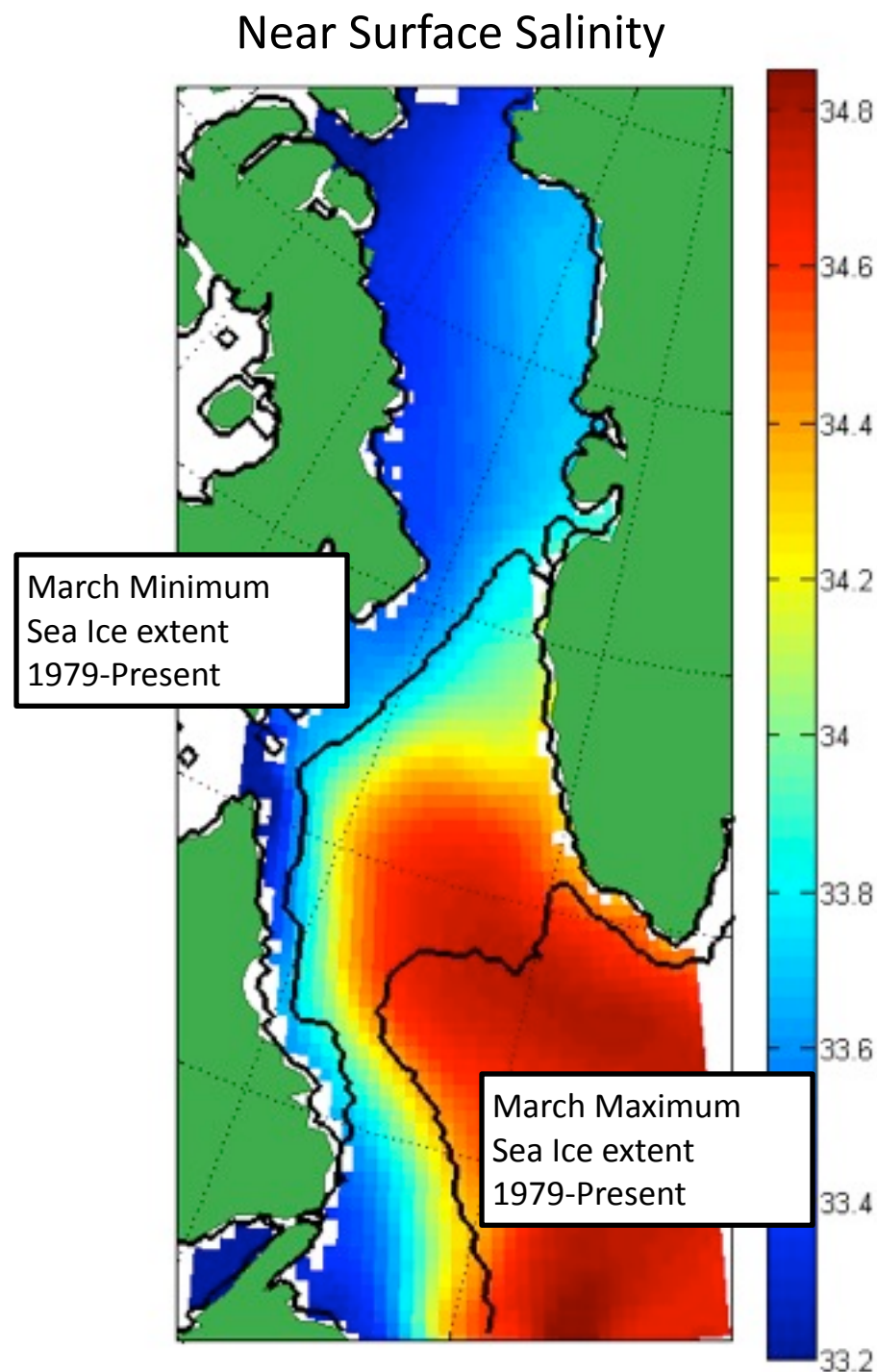
- Sea Ice Annual Cycle
- Hydrography
- Ice transport
- NAO
- Salinity Anomalies

Seasonal sea ice interannual variability is dominated by wintertime extent thereby implicating atmospheric and oceanic variability.

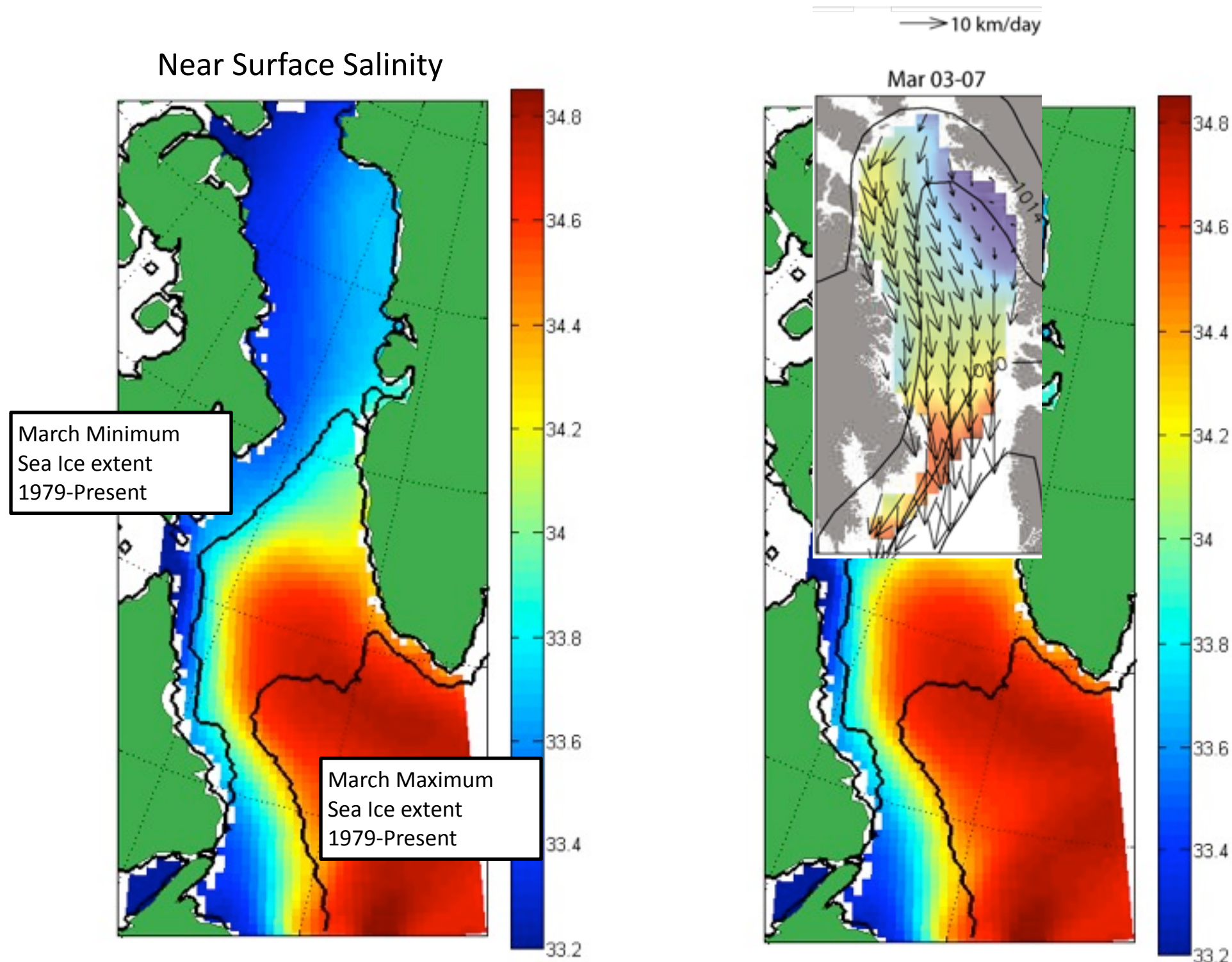


Example cycle 1995/96

# Ice extent maxima variability coincides with Arctic Water and Irminger Water Thermohaline Front on the Northern Slope.

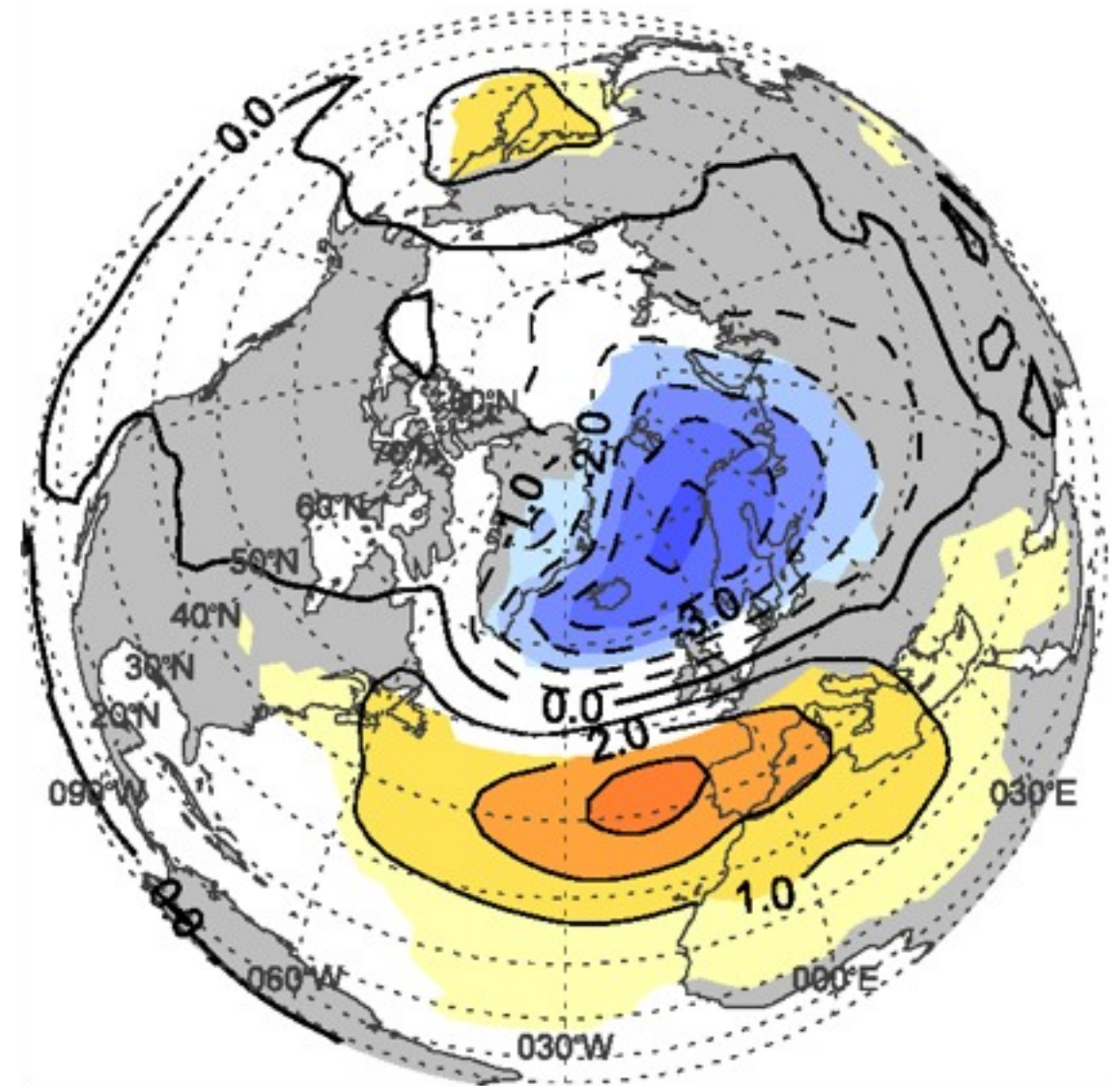
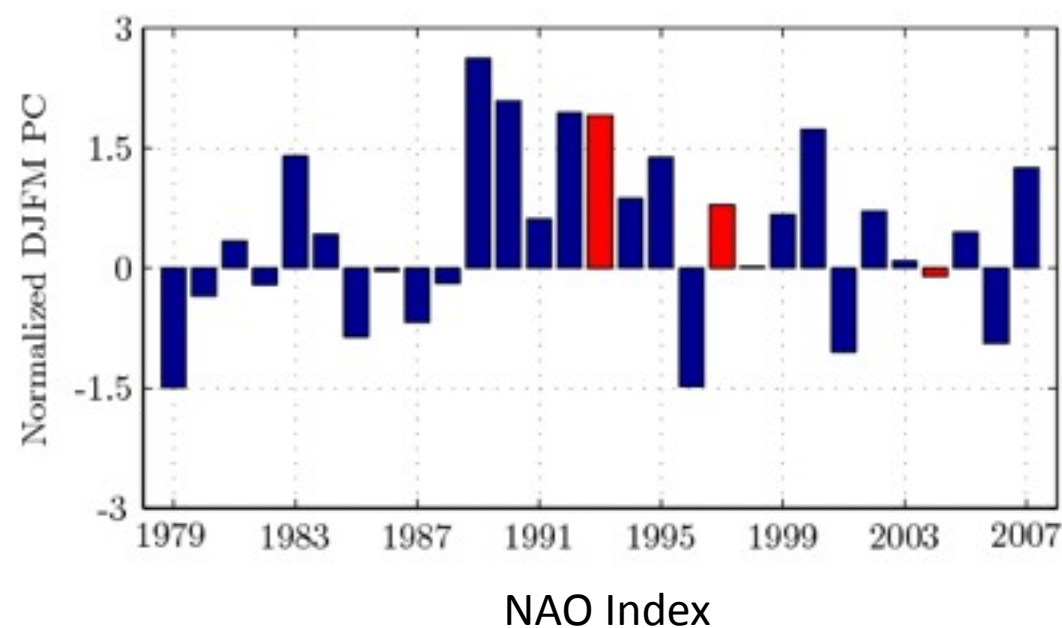
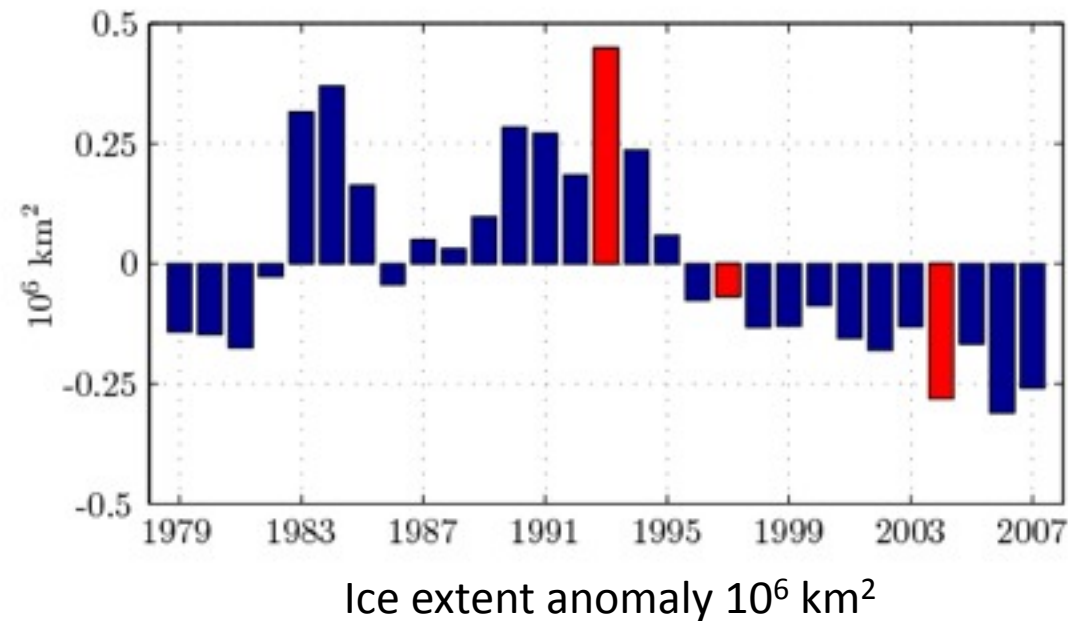


Sea ice drifts through Davis Strait across the THF into the region of interannual extent variability.



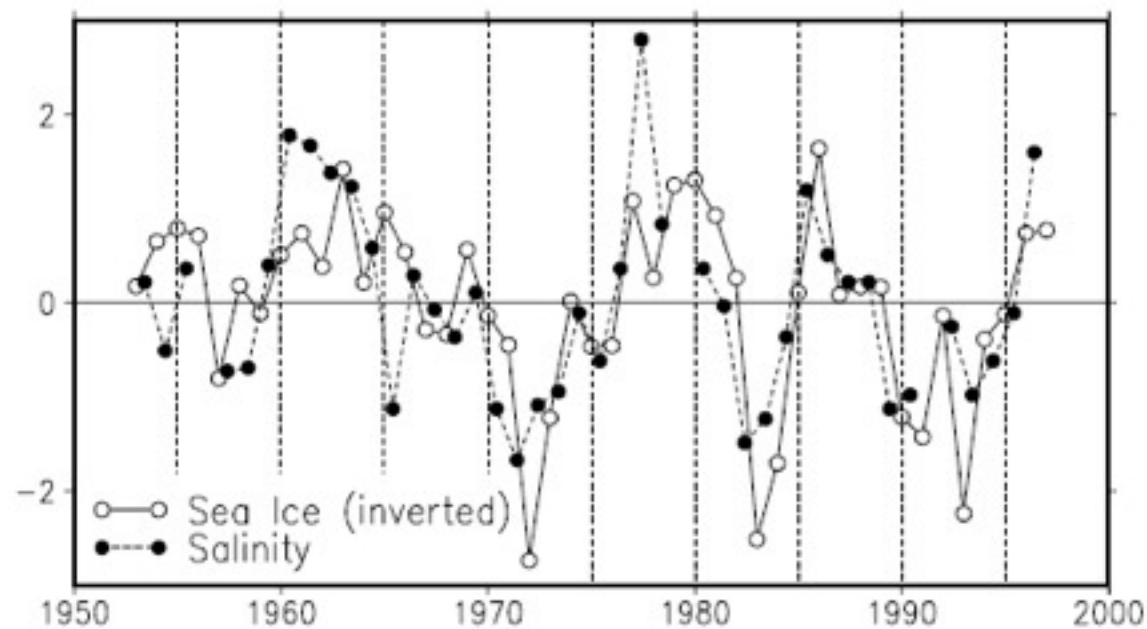
(Ice drift from Kwok 2007)

Seasonal ice extent anomalies in the Labrador Sea are correlated with the NAO with recent exceptions.

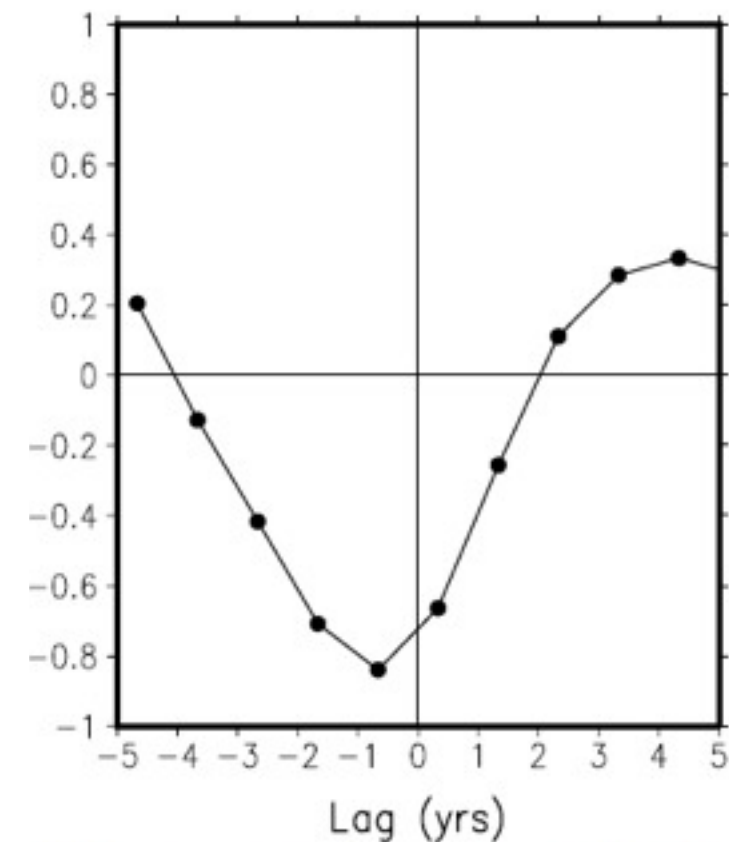


SLP anomalies (hPa) associated NAO index

Negative near-surface (upper 100 m) salinity anomalies lead positive sea ice extent anomalies in the northern Labrador Sea.



**Figure 15.** Inverted winter Davis Strait ice index (open circles) and April–July salinity anomalies at 100 m depth in the West Greenland Current (offshore of Fylla Bank; solid circles). Both curves are normalized by their respective standard deviations, and no temporal smoothing has been applied other than seasonal averaging.



Lag cross-correlations: salinity/sea Ice  
Negative → salinity record leads ice index

# Theories of Labrador Sea Ice Variability: Summary

- Atmosphere-centric
  - Offshore winds → ice transport across THF
  - Heat flux → ice production
  - NAO
- Ocean-centric
  - Low salinity anomalies → *in situ* ice growth
  - Subpolar gyre/Arctic freshwater anomalies
- Connection between hydrographic and sea ice variability still not well understood...

# Part II: The synthesis of model and data

- State Estimation
- Model description
- Observations
  - *In situ + remote*
  - *Hydrographic*
  - *Ice concentration*
- Model-data consistency
  - Ice concentration, extent
  - Wintertime mixed layer depths

# Methodology: Adjoint Method

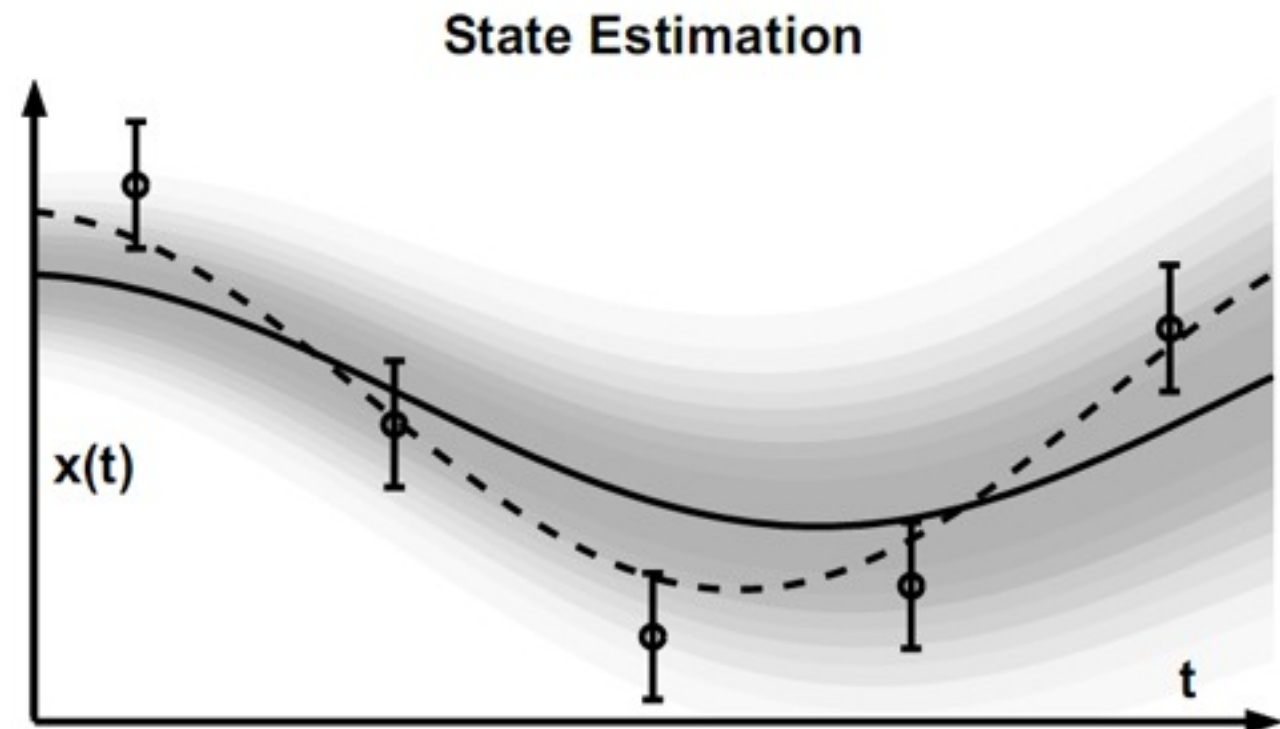
Goal is to generate a dynamical reconstruction of the three dimensional time-varying ocean-sea ice system : state estimate

Essentially , a least-squares fit between model state and observations.

System evolves on the merits of the physics and thermodynamics encoded in the numerical model given *initial* and *boundary* conditions

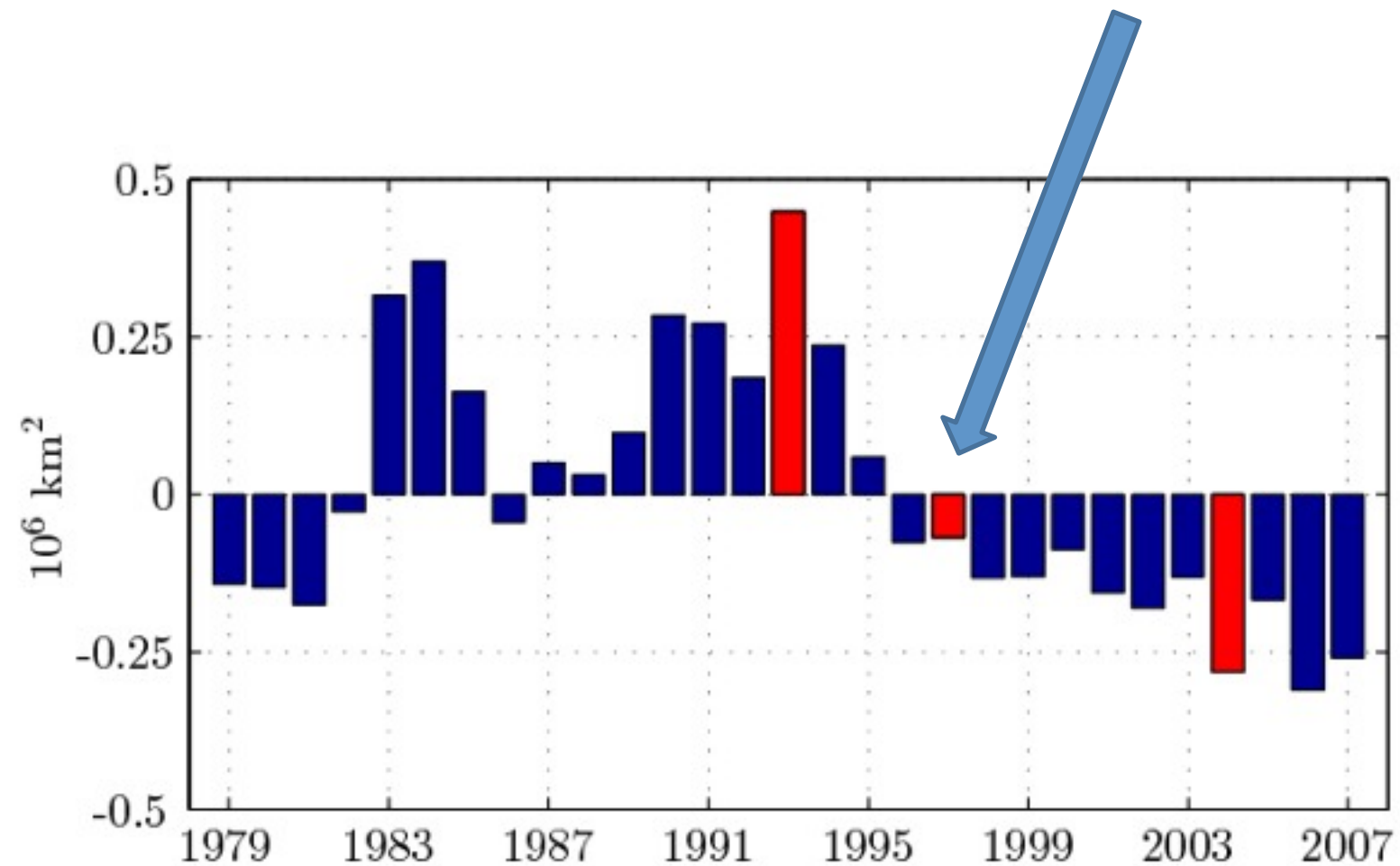
Iteratively adjust *initial* and *boundary* conditions using information provided by the Lagrange multipliers (adjoint variables) of the system, as provided by model adjoint

Novelty : include *sea ice concentration* observations with a thermodynamic sea ice adjoint model.



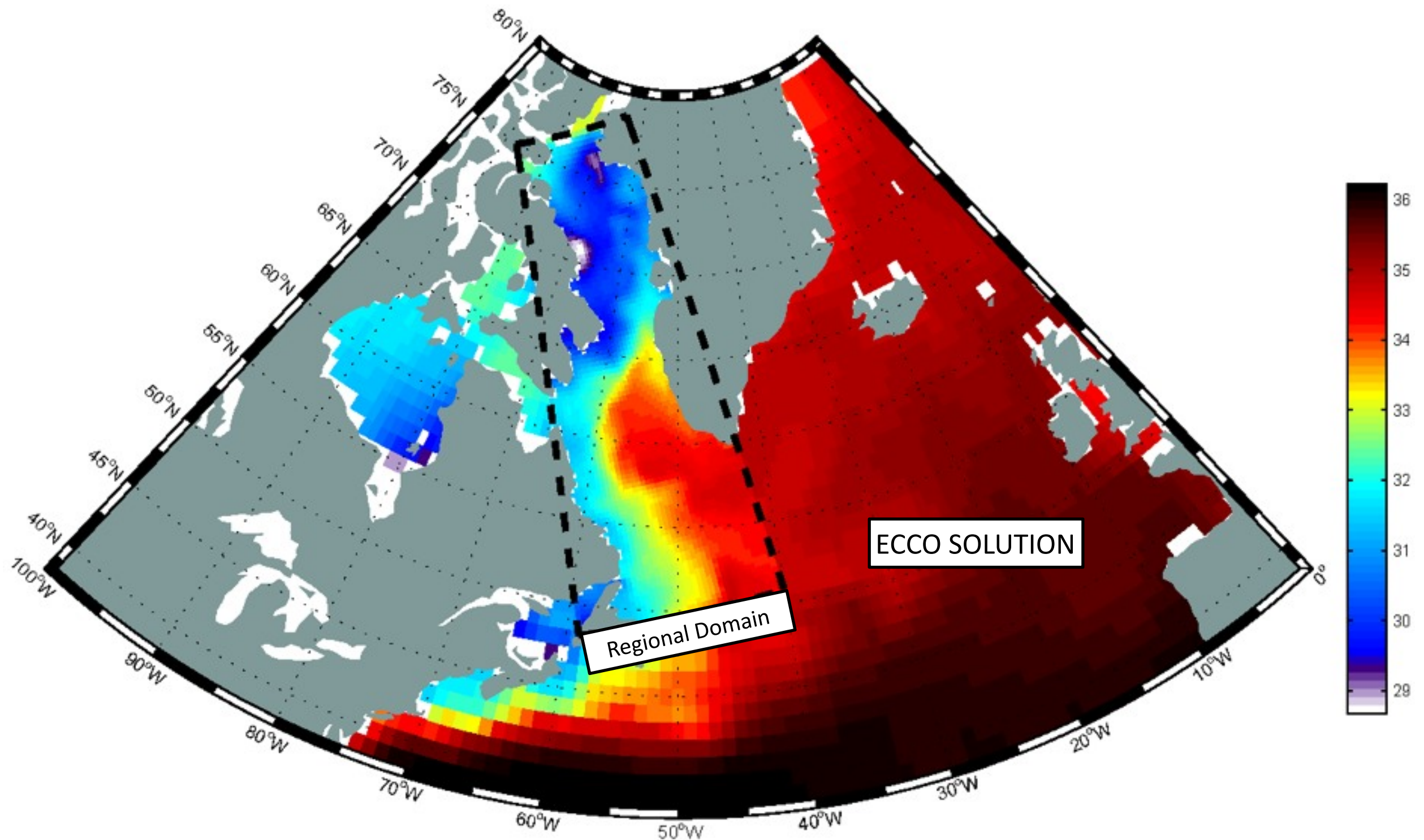
Circle/bars : observations + uncertainties  
Solid : initial state trajectory  
Dashed : improved state estimate

Today I focus on the 1996-1997 sea ice annual cycle.



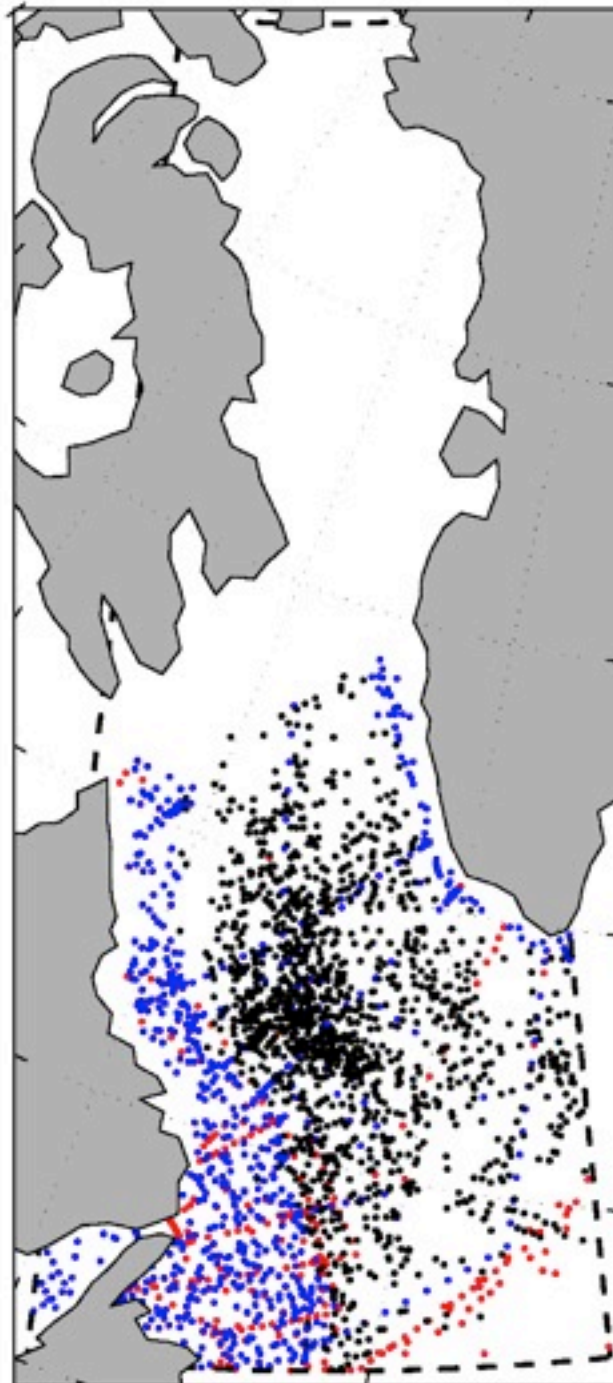
Ice extent anomaly

The 1/3-degree regional model is one-way nested inside the 1-degree ECCO solution.

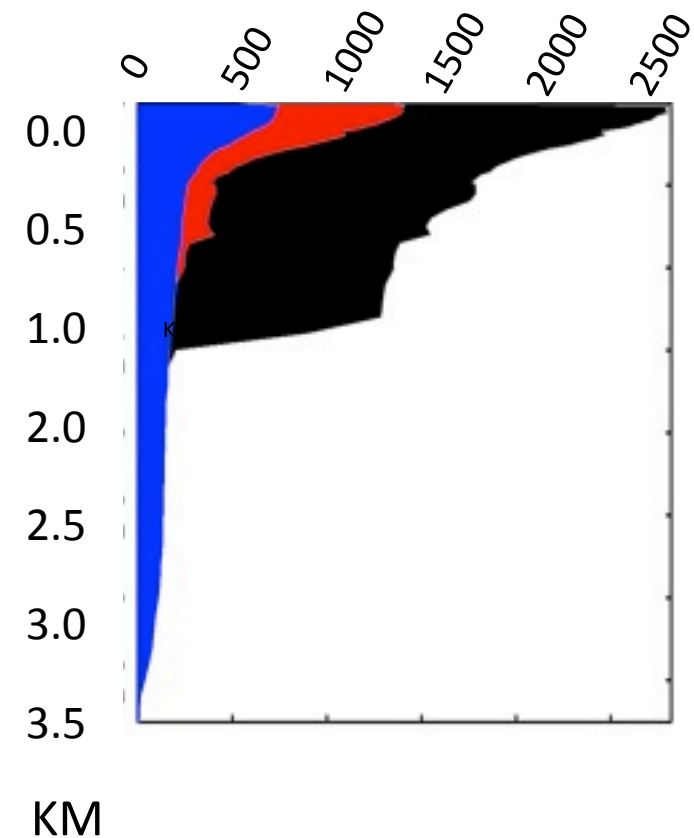


Ocean observations during 1996-1997 annual cycle are particularly numerous.

*in situ* ocean  
observation locations



Number of Observations  
with depth



Blue = CTD  
Red = XBT  
Black = Profiling Floats

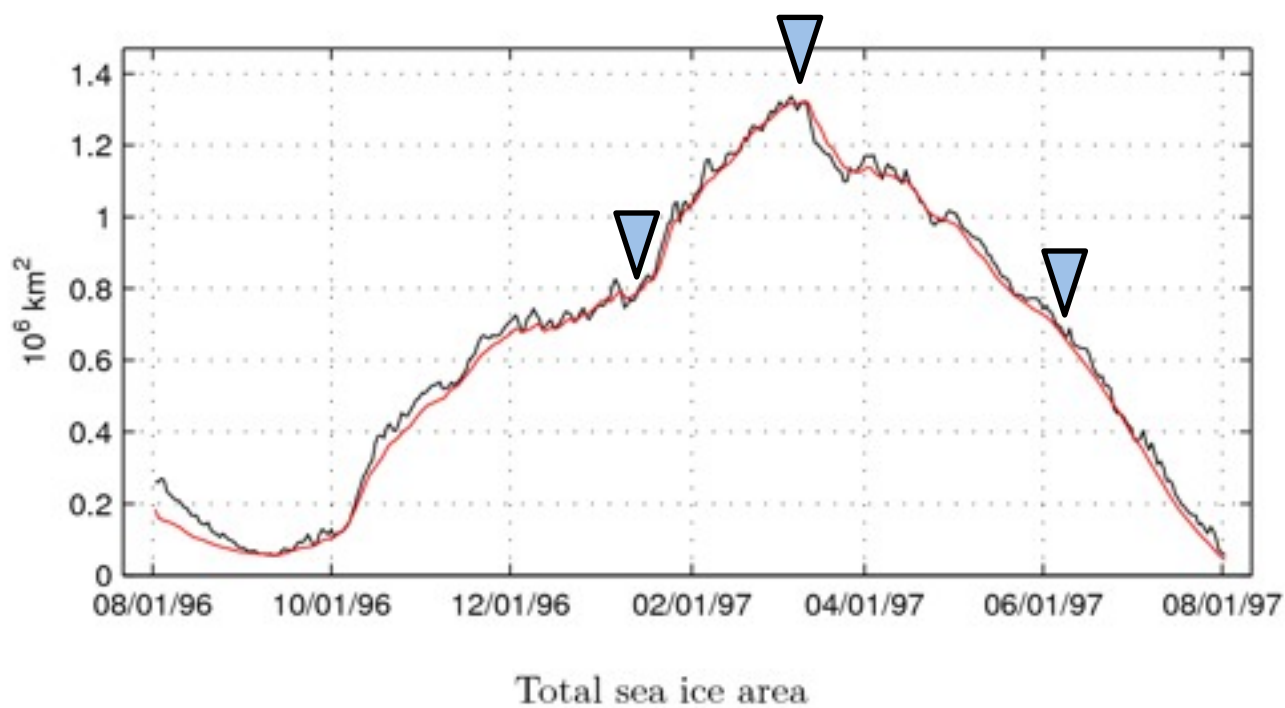
# Synthesized Ocean + Ice Observations

[Aug 1996 –Aug 1997 ]

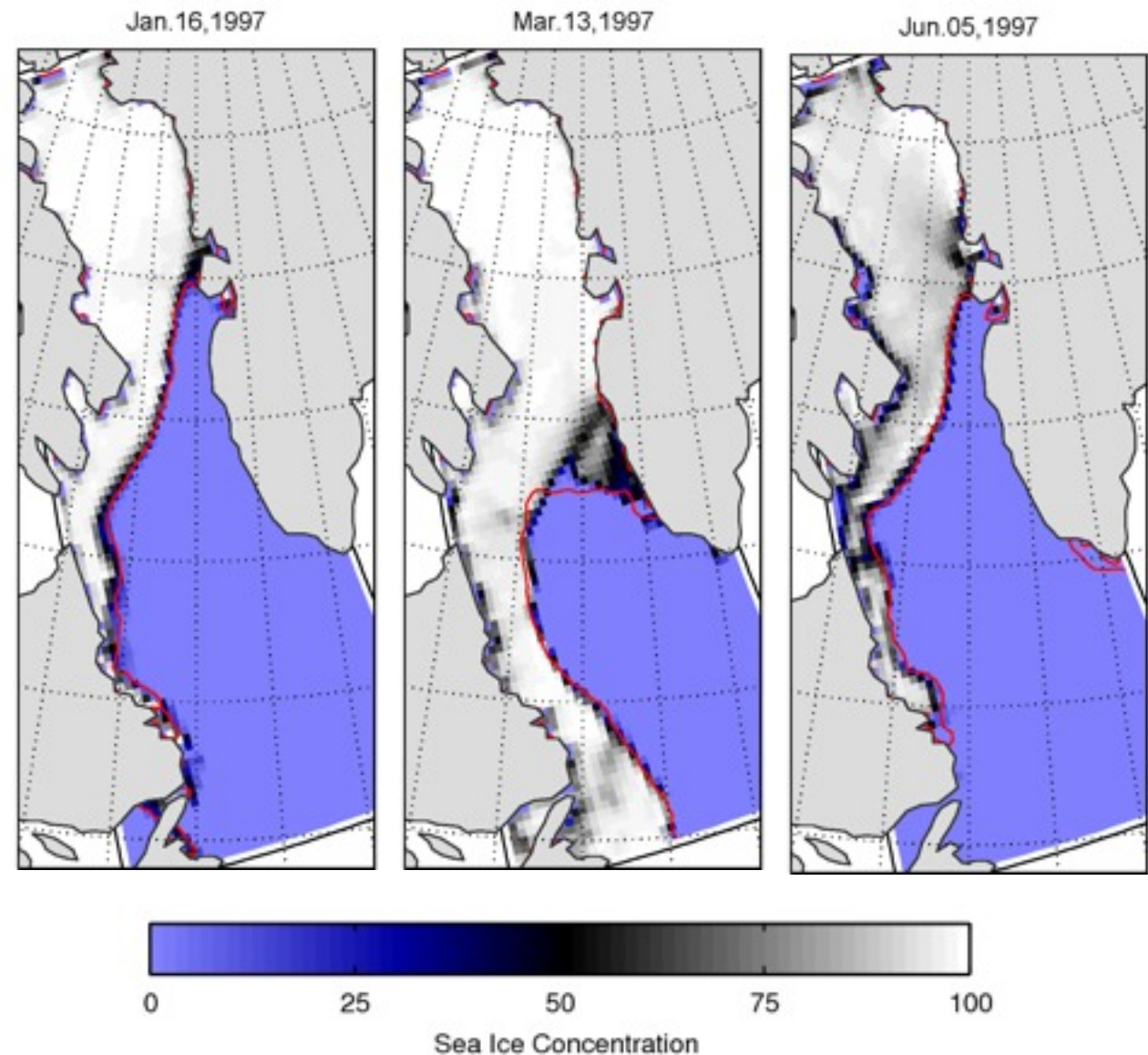
	TEMPERATURE	SALT	ICE CONC.
CTD / XBT / Profiling Floats	105	73	
Reynolds ¼-degree SST	680		
Ocean T and S Climatology	422	422	
Ice concentration from SSM/I	1048		1048
Total	2255	498	1048

# of observations (x10<sup>3</sup>)

The reconstruction of sea ice concentrations, extent, and total integrated area are consistent with data.



Black: Observations  
Red: State Estimate



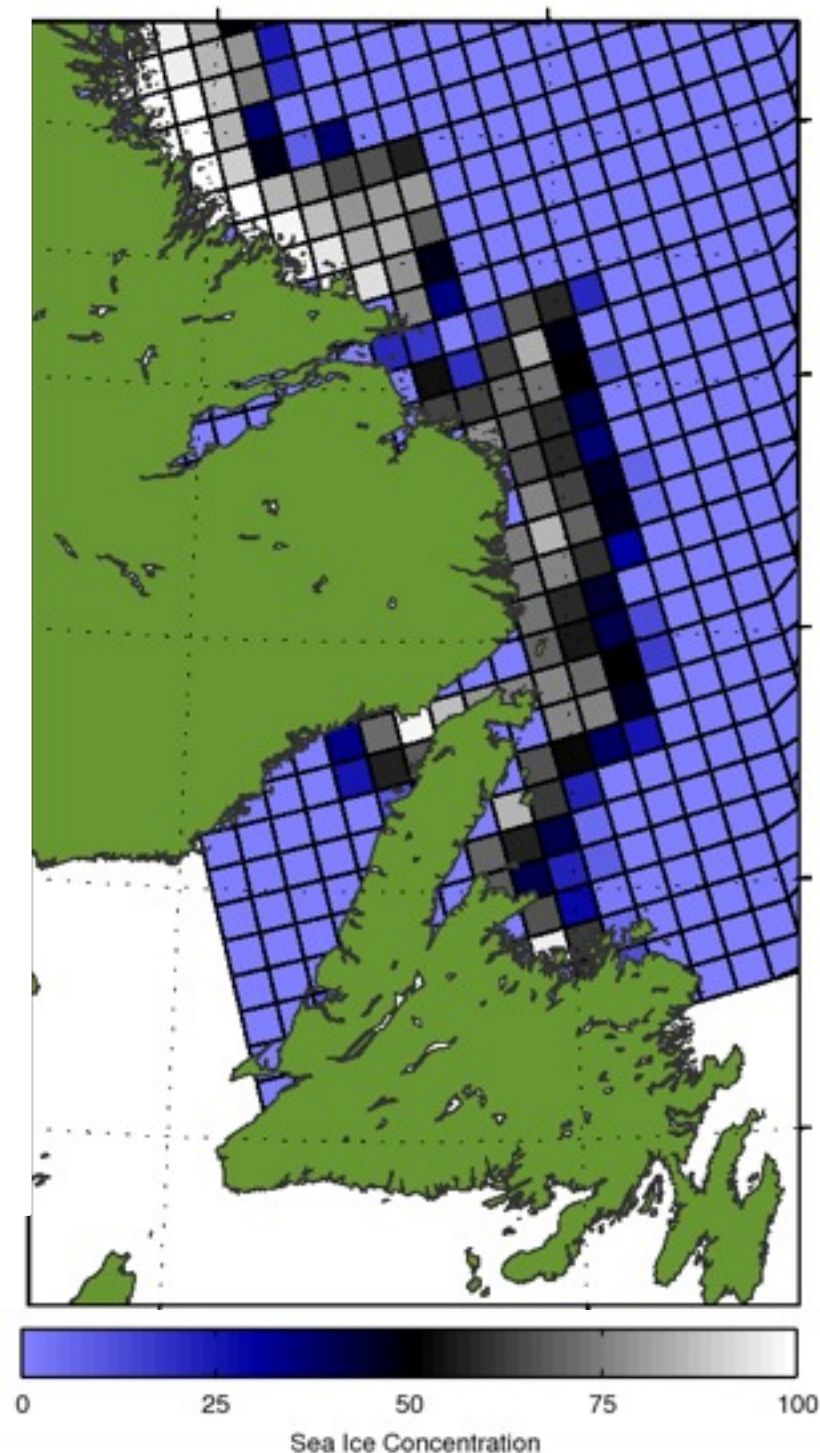
Red line: 15% Observed Ice Concentration

# The representation of sea ice is limited by the resolution of the data and model.

4.5 km MODIS Image



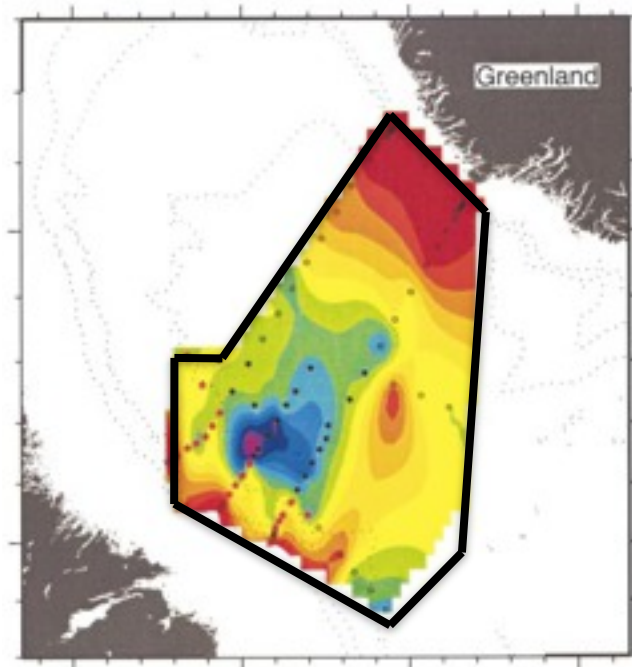
25 km SSM/I product



# Reconstruction of southwest Labrador Sea

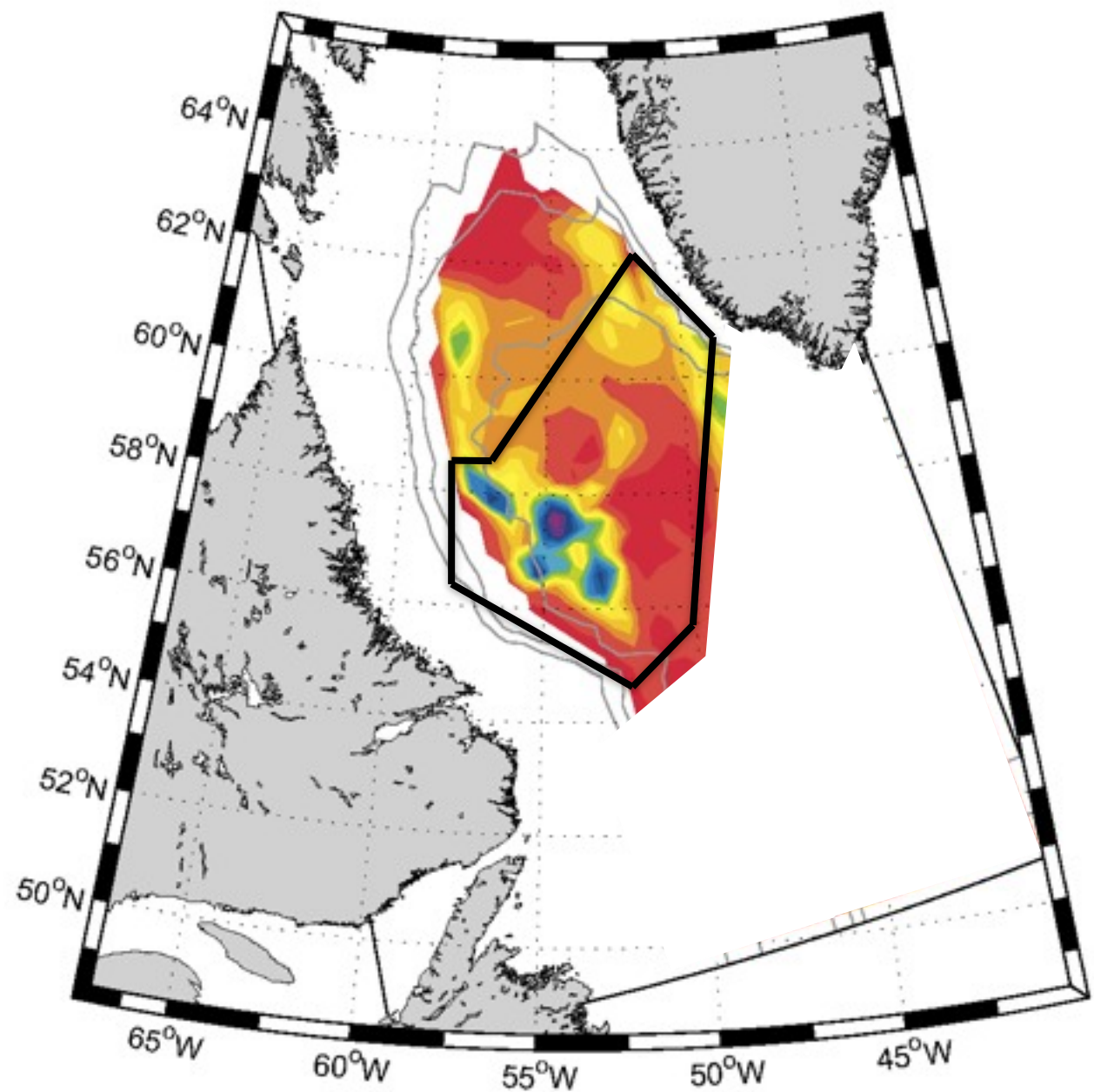
MLD are consistent with data.

Interpolated from CTD



Feb 97 – Mar 97

State Estimate MLD

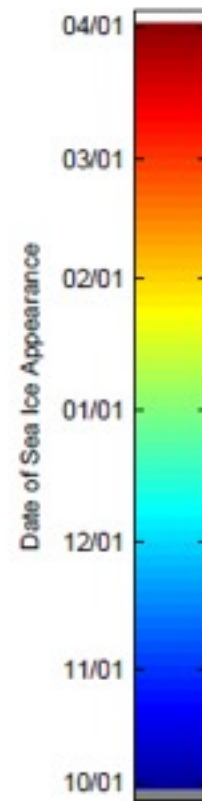
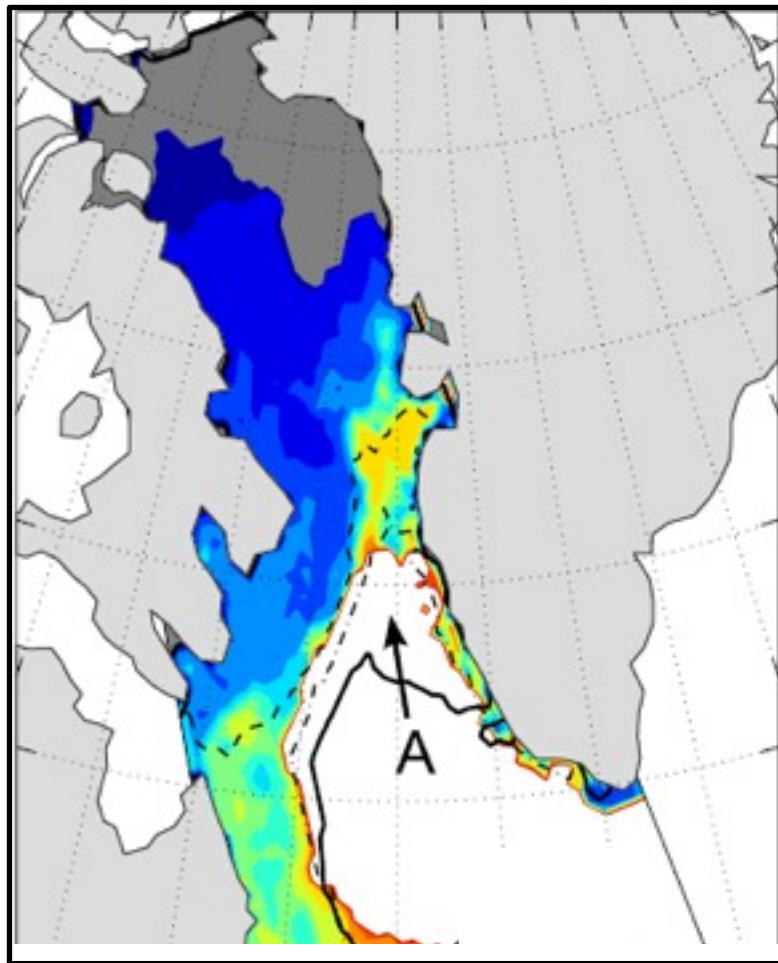


# Part III: Hydrographic and sea ice variability in the Labrador Sea : 1996-1997

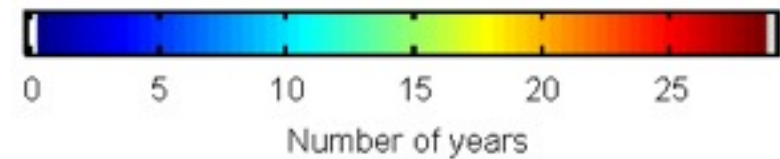
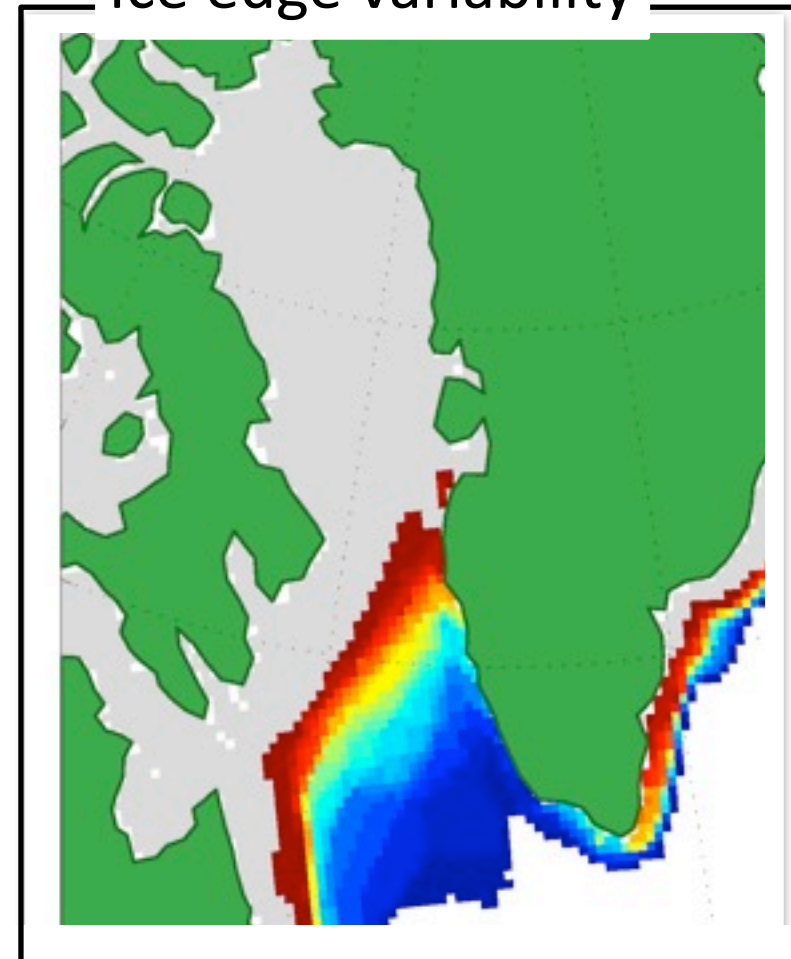
- Lateral tracer/ice transport and ice edge
- Evolution of Ice Edge Position
- Ice Mass Budget
- Role of buoyancy forcing on the evolution of the ice edge
- Ice Buoyancy Budget

Sea ice does not develop on across the THF without lateral ice/ocean tracer advection.

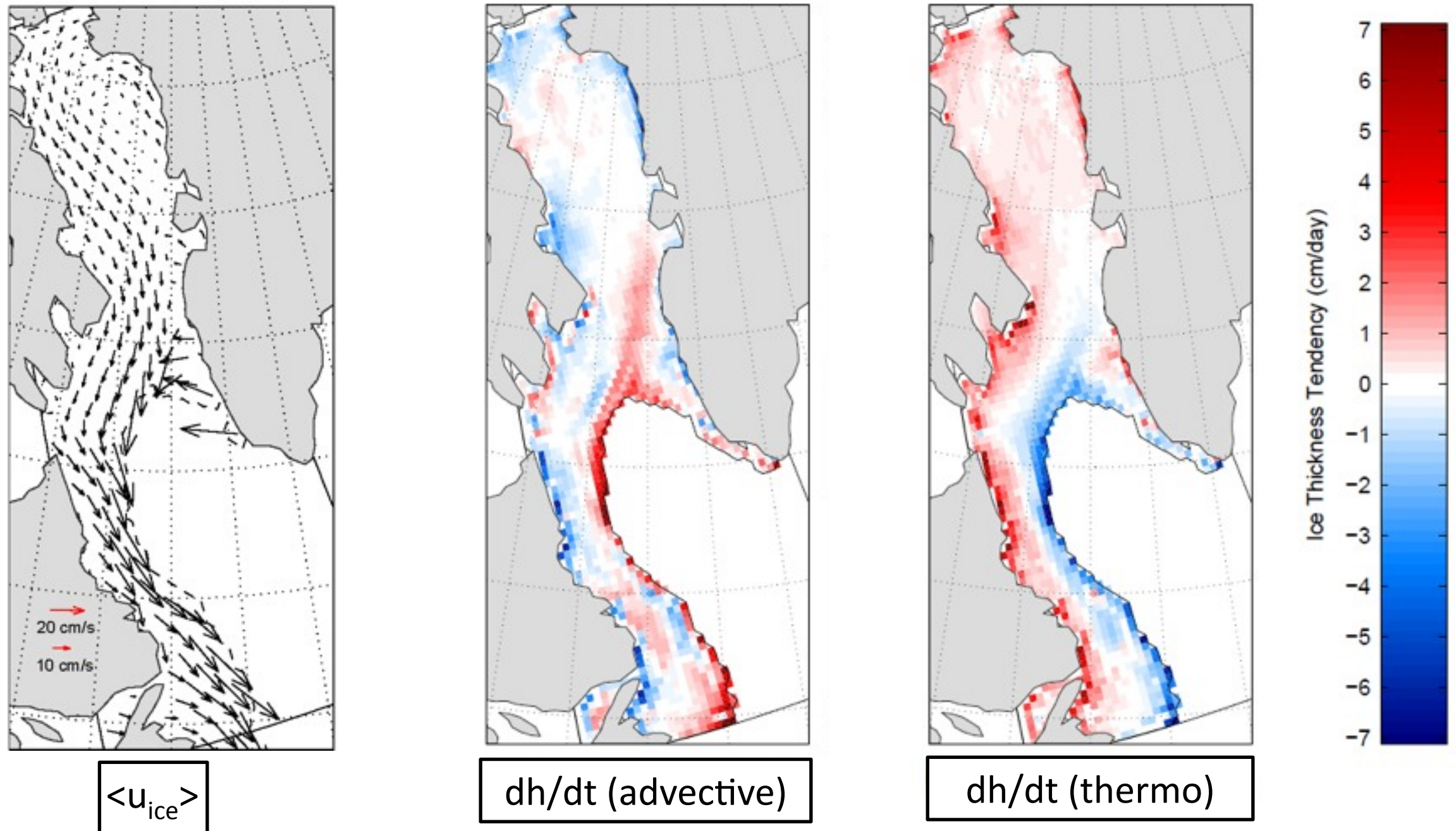
Ice edge with 1-D processes



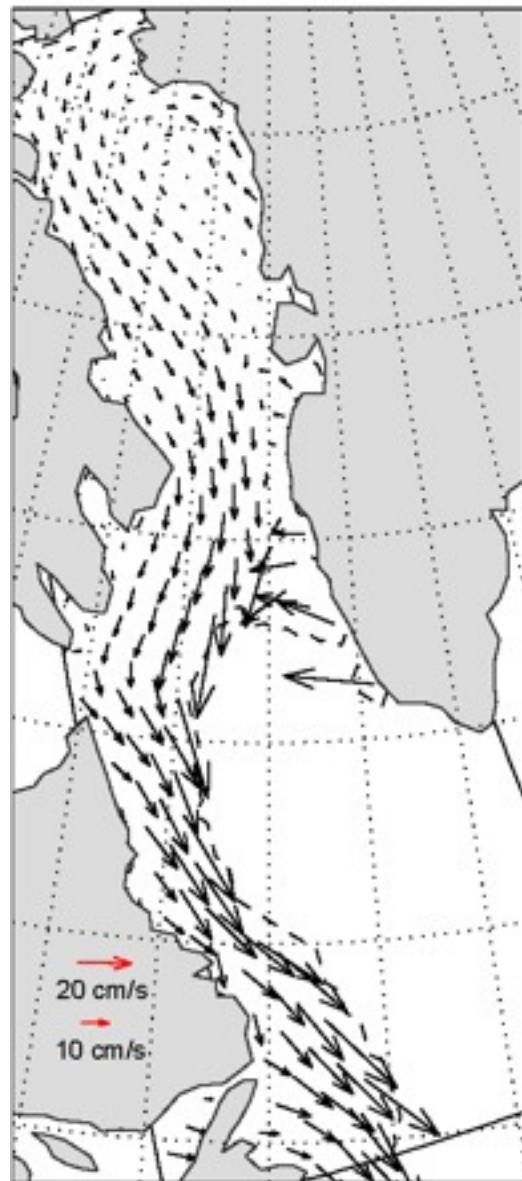
Ice edge variability



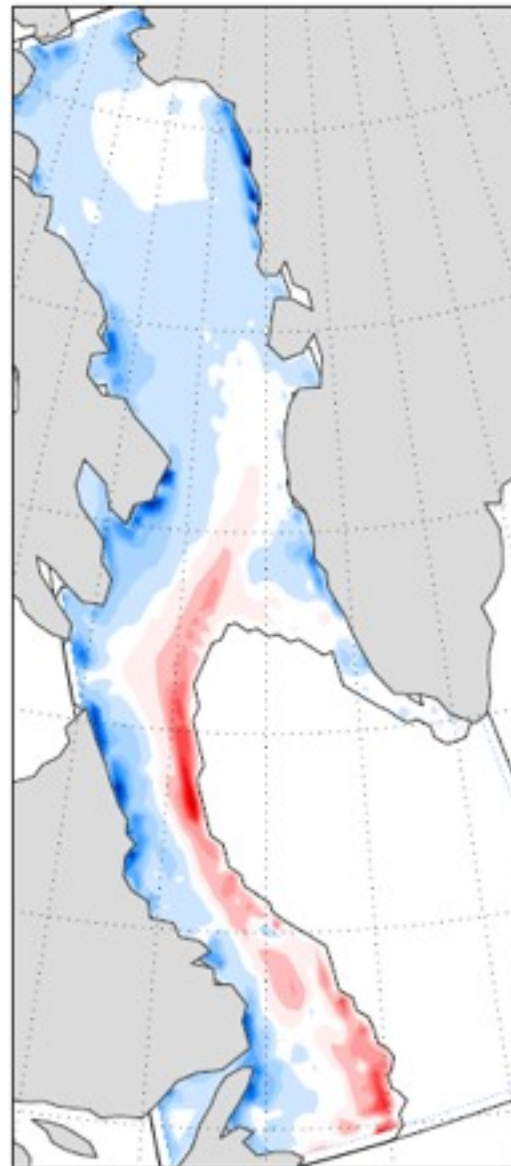
# Sea ice quasi-equilibrium established with near-coastal production, lateral transport, and MIZ erosion



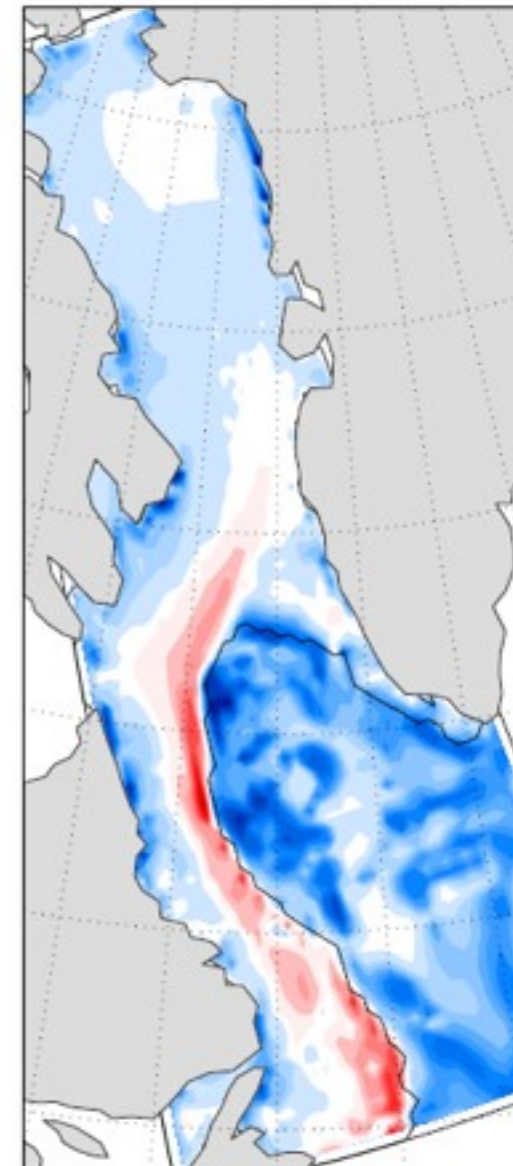
Ocean buoyancy fluxes from positive ice meltwater are comparable in magnitude to negative air-sea heat loss.



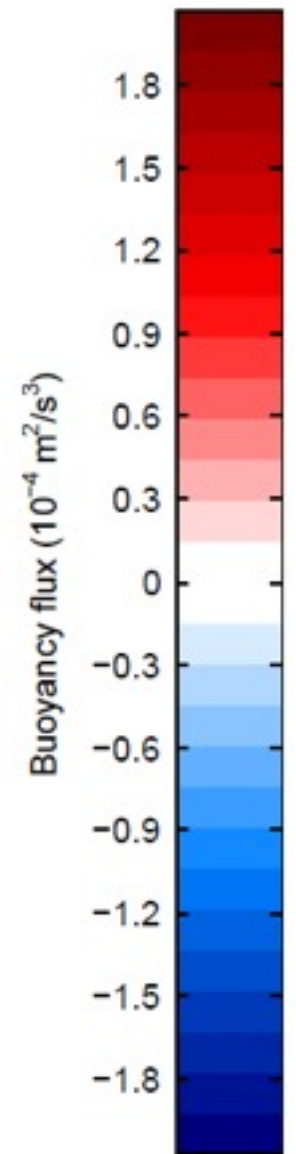
$\langle u_{ice} \rangle$



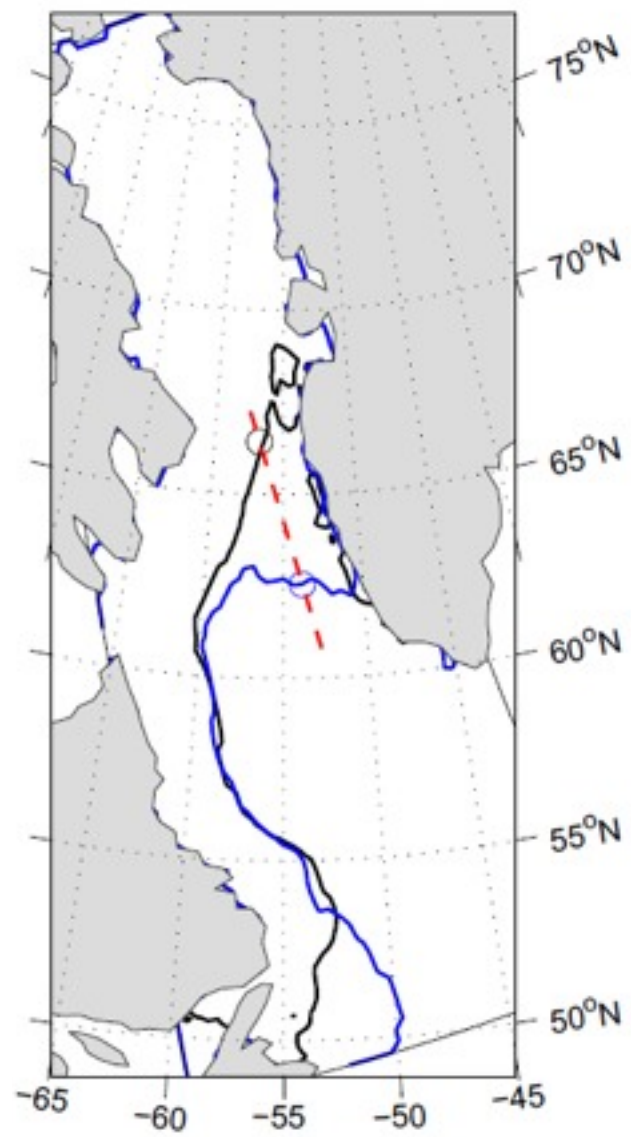
Ice buoy flux



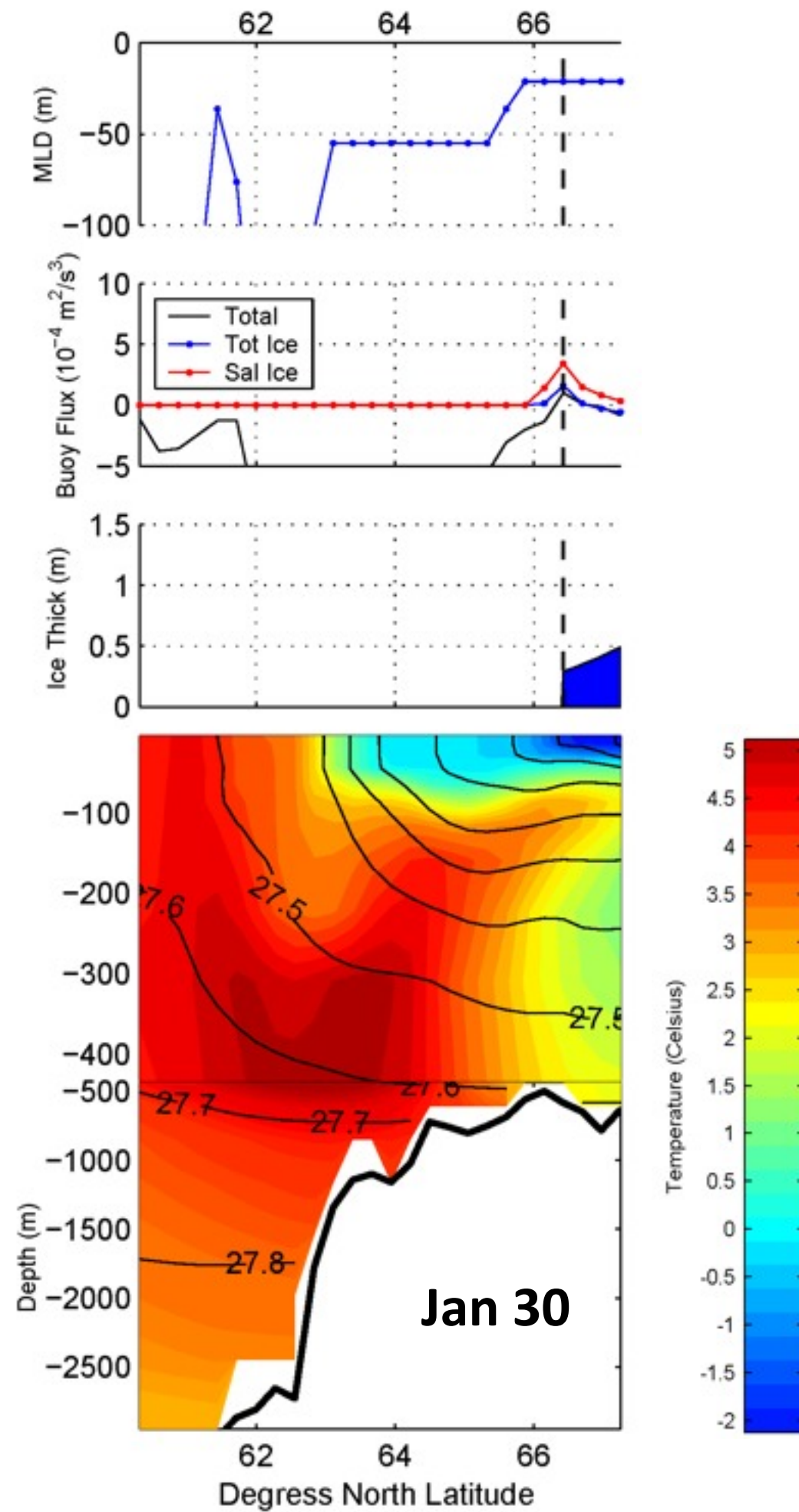
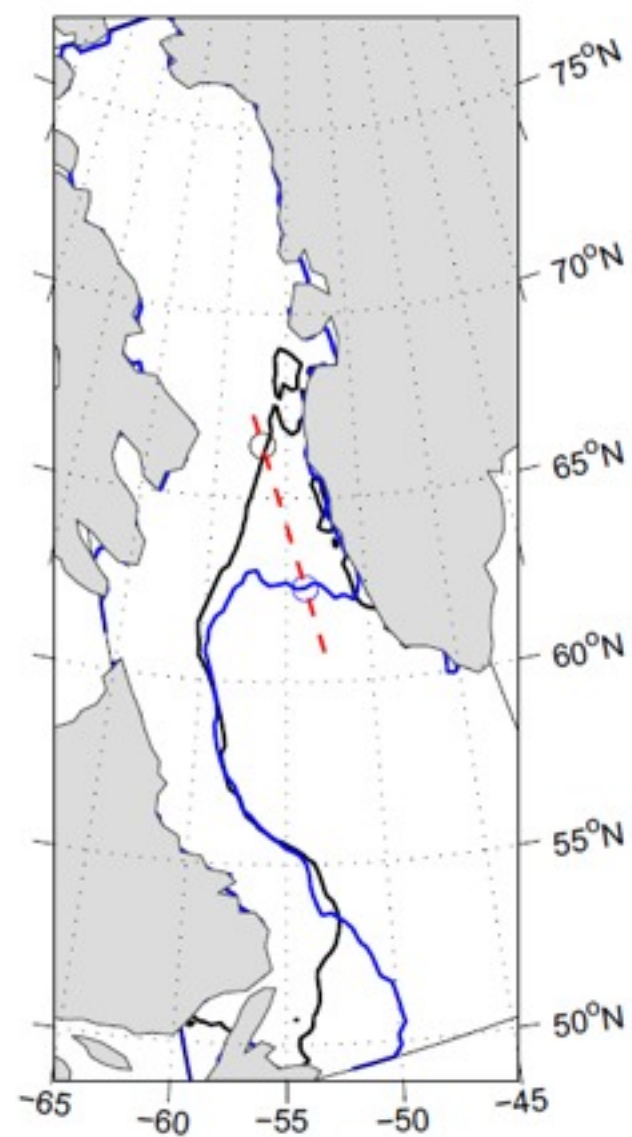
All buoy flux



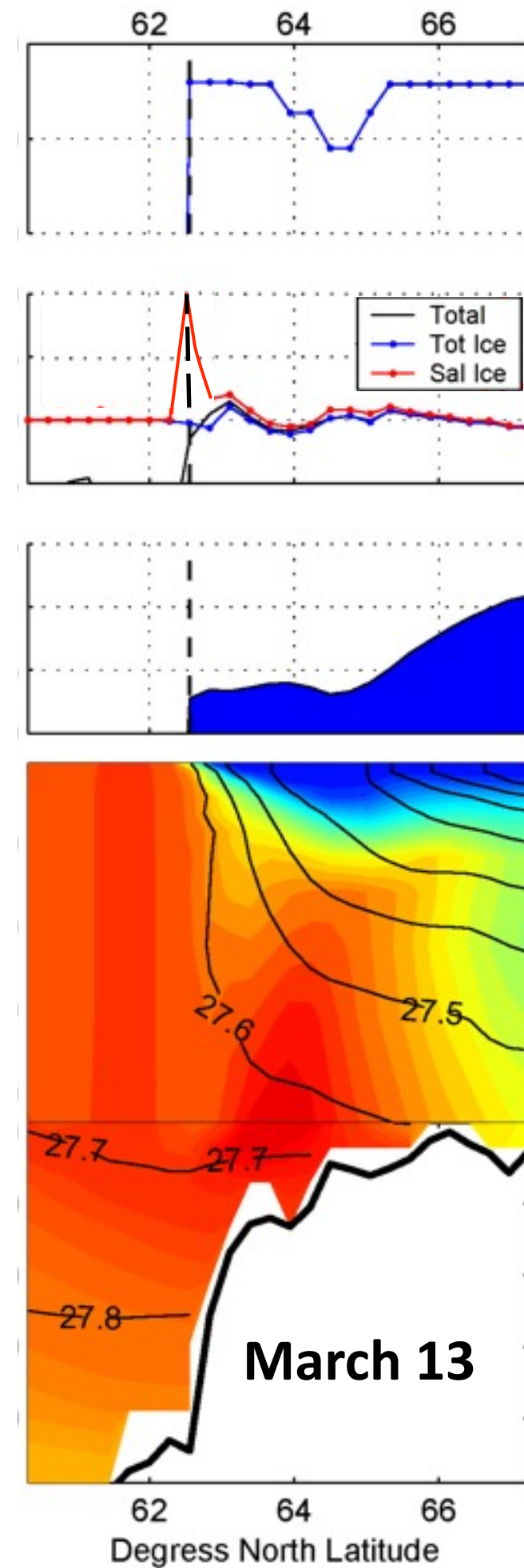
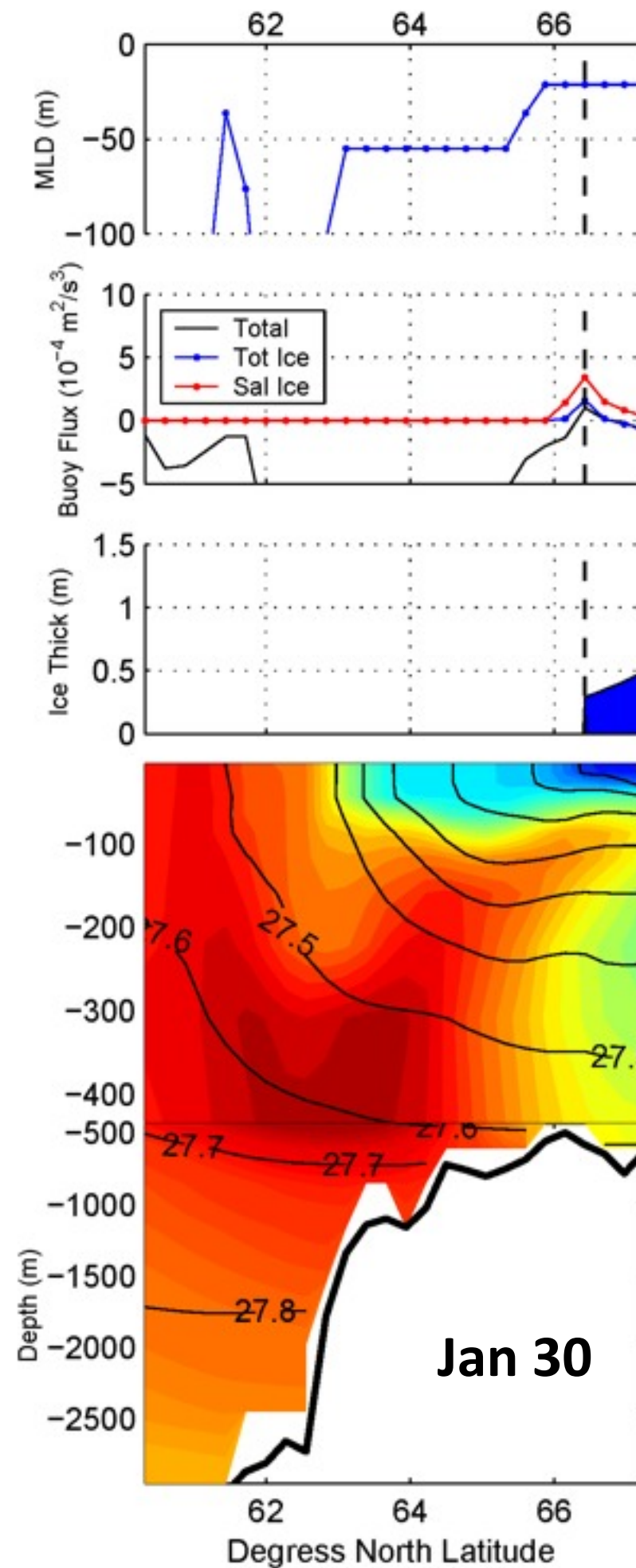
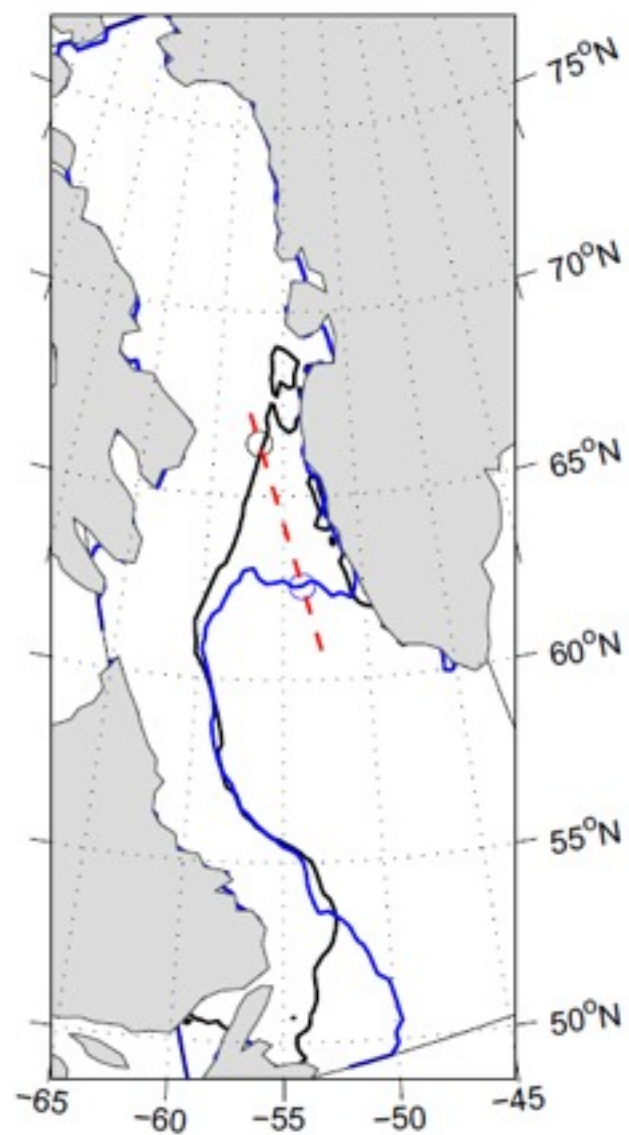
**Sea Ice edge**  
**Jan 30 + March 13**



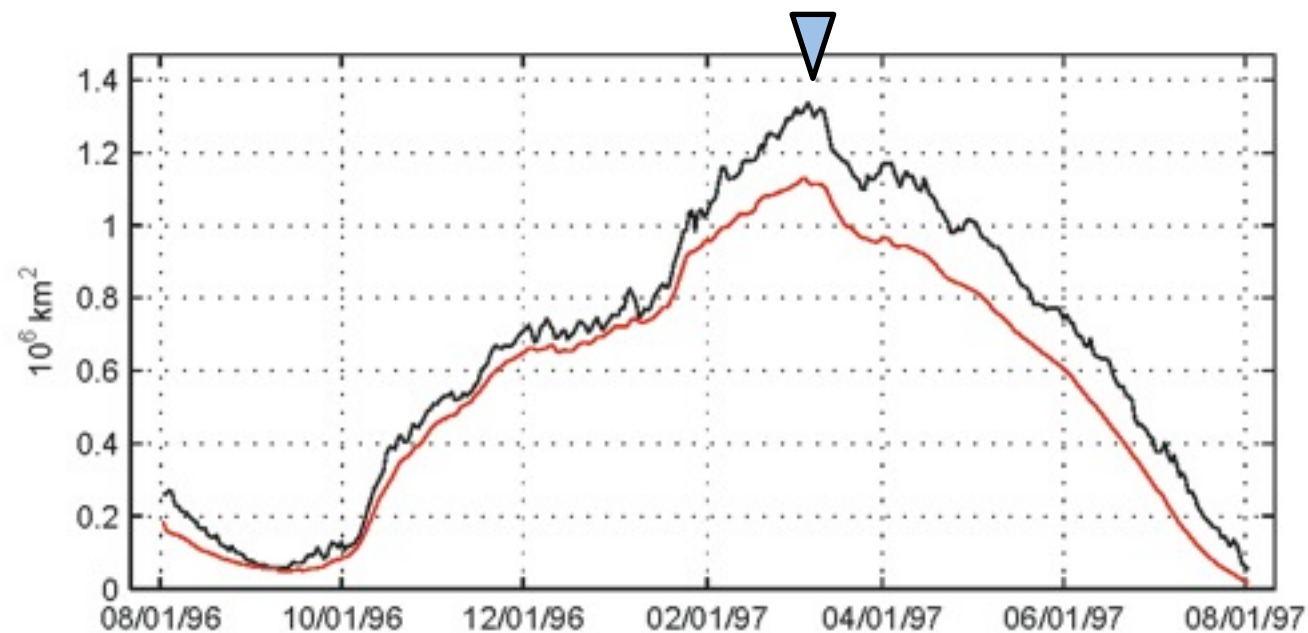
# Sea Ice edge Jan 30 + March 13



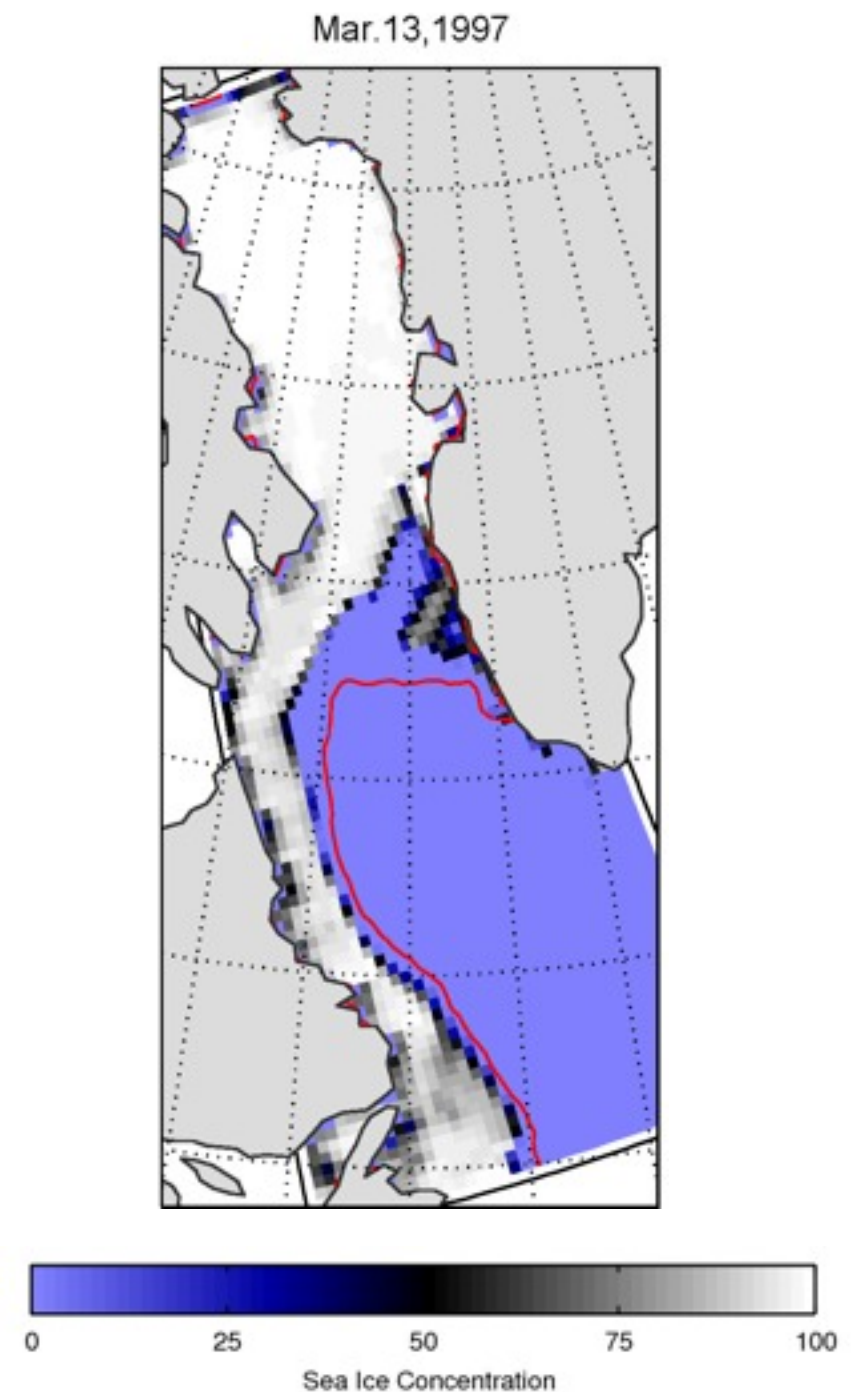
**Sea Ice edge**  
**Jan 30 + March 13**



Sea ice does not fully extend across the THF without the positive buoyancy forcing from meltwater release.

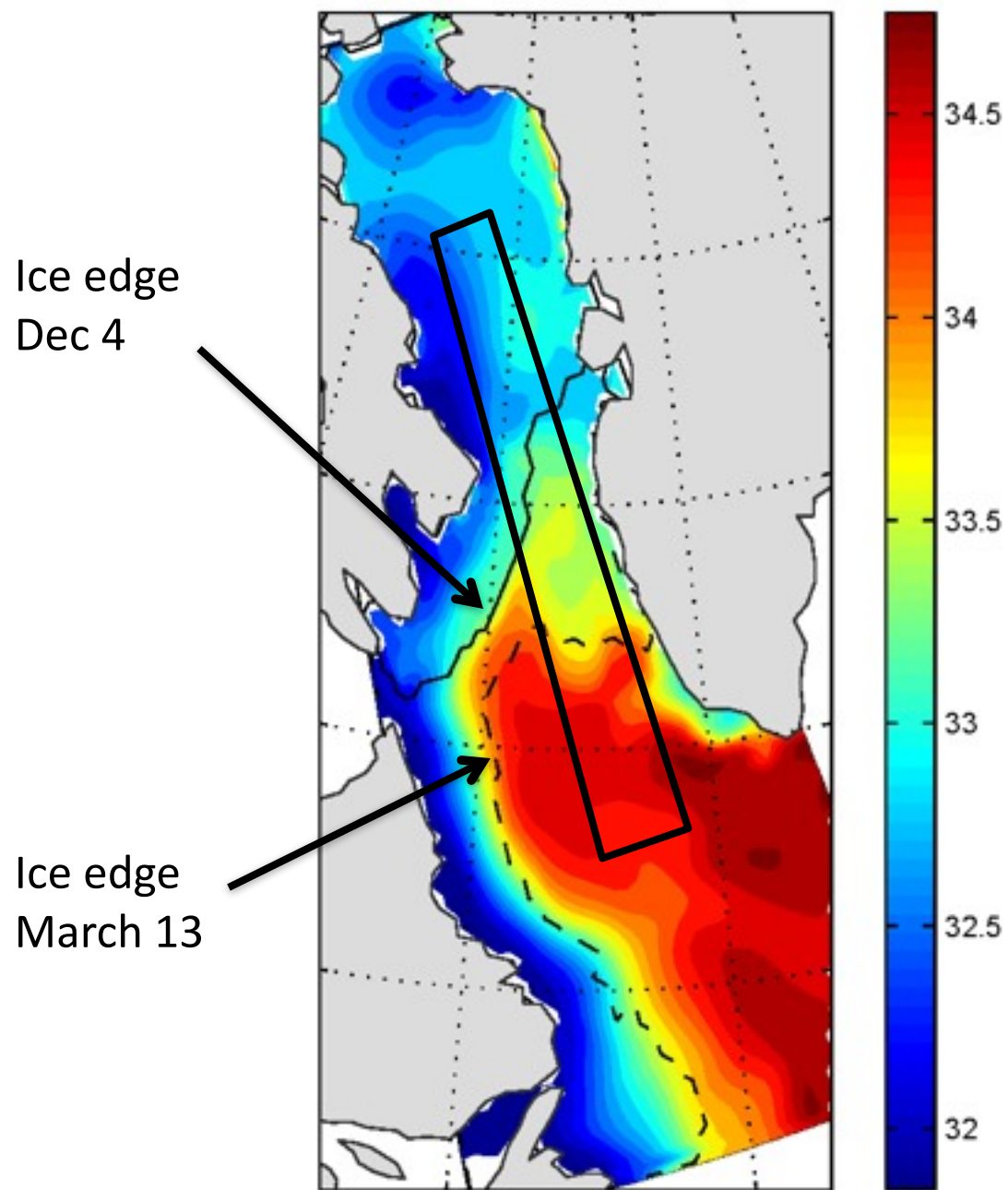


Black: Observations  
Red: State Estimate

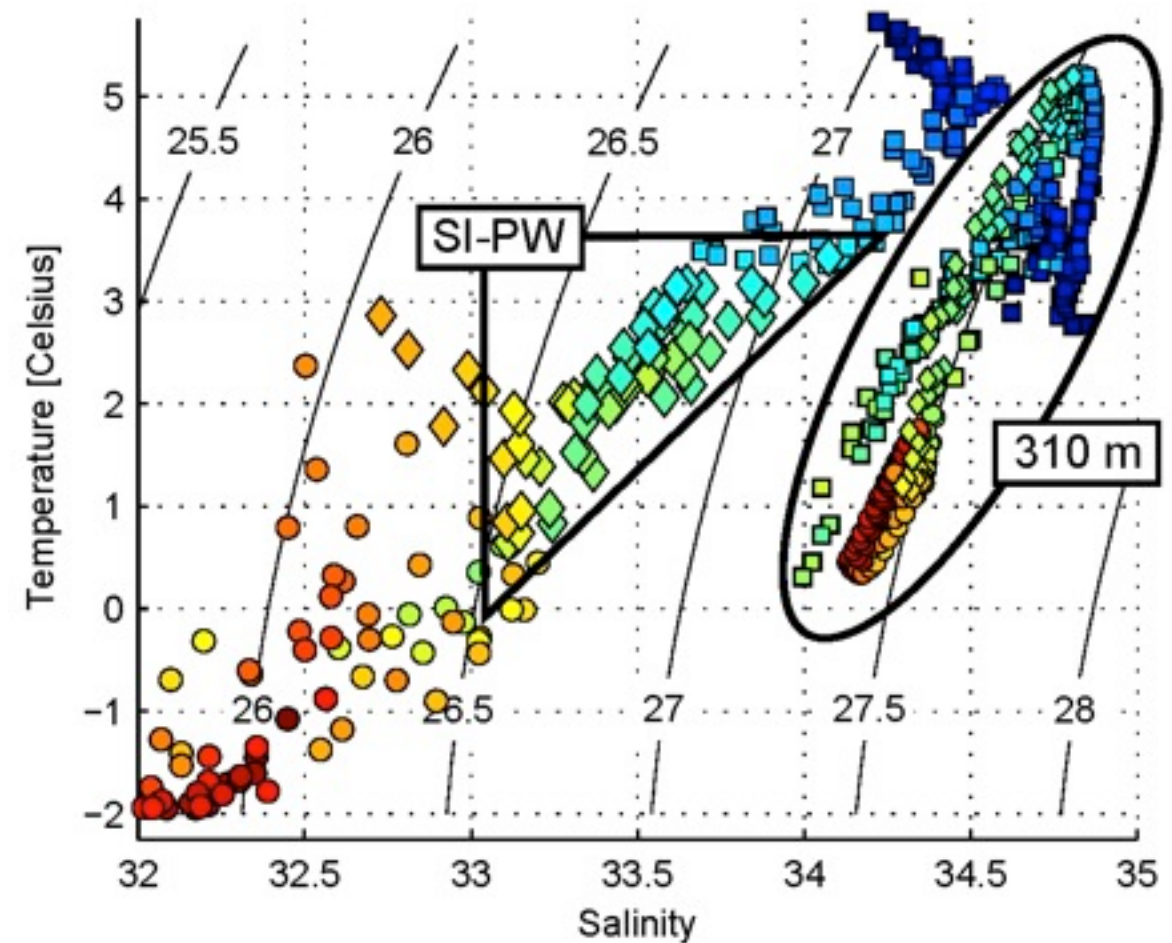


Red line: 15% Observed Ice Concentration

Sea ice-preconditioned waters are sufficiently fresh to prevent convective entrainment of warm subsurface waters.



Dec 4, Salinity @ 20 m



October 13, 1996

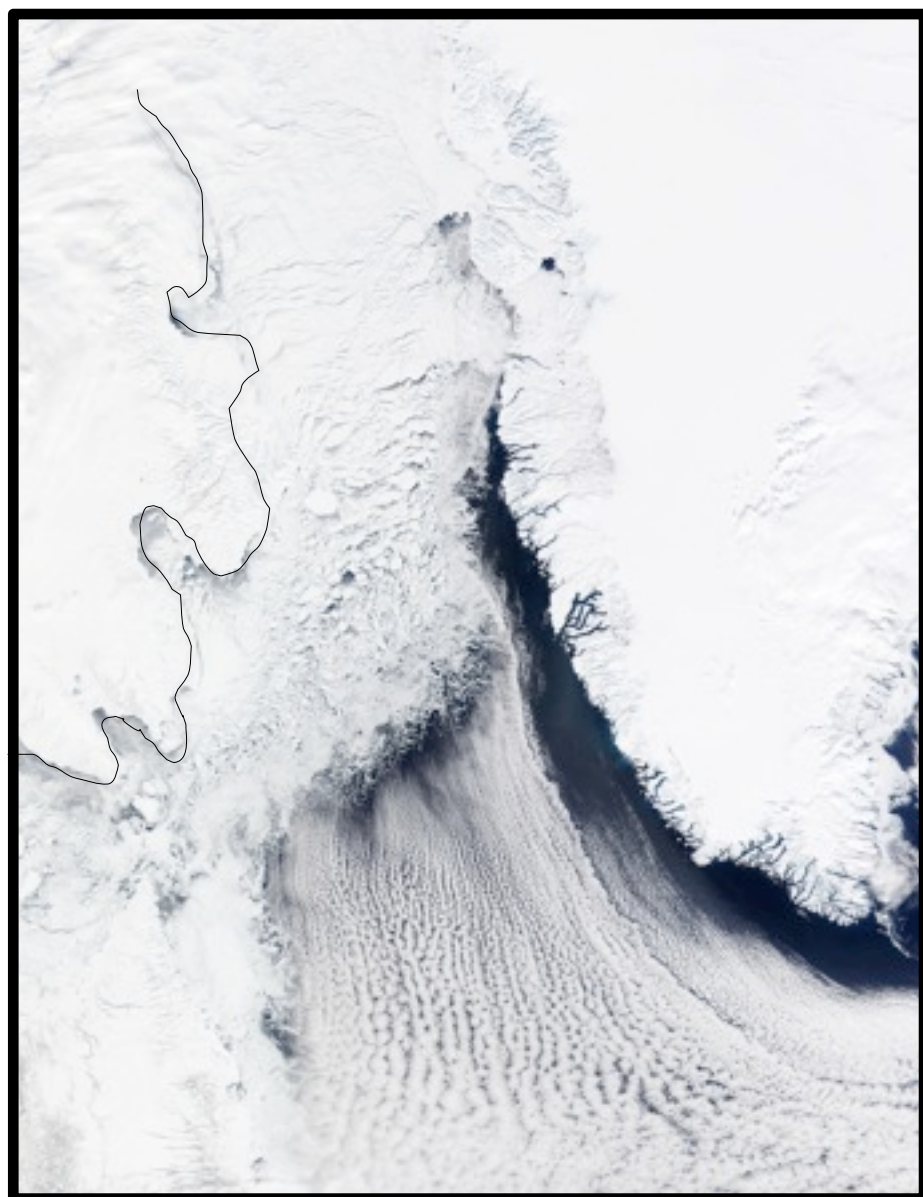
# SUMMARY AND NEXT STEPS

# Summary

- Extending the ECCO global ocean state estimation project, a regional ocean-sea ice model has been brought into consistency with *in situ* and satellite-based observations of ocean temperature and salinity and sea ice concentration.
- Analysis of the state estimates reveals a probable first-order role of upper ocean hydrographic state in setting limits on sea ice extent in the Labrador Sea.
- Low salinity anomalies across the THF are insufficient for local sea ice growth – sea ice meltwater release is required to stabilize the mixed layer first.

# Next steps...

- Continue the study of high-latitude hydrographic and sea ice variability
  - Origin of sea ice preconditioned waters
  - Analogue in other marginal seas
  - Predictability of seasonal sea ice maximum
- Next generation ECCO model
  - Arctic/North Atlantic @ 7 km
  - Advanced subgrid scale ocean parameterizations
  - Improved sea ice model (enthalpy storage, multi-category, salt plumes)
- Synthesis of Additional Data
  - Snow + Ice freeboard from ICESat
  - ULS of ice draft (e.g. Fram Strait, NPEO, ice-mass buoy)
  - Sea ice velocity reconstructions
  - Ice-tethered CTD profiles
  - Atmospheric estimates of better quality for polar regions



MODIS Image

